Seeding of oak in southern Sweden

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Abstract

Sweden is known for its coniferous forests, but two oak species occur in the south, *Quercus robur* and *Q. petraea*, in pure stands or mixed with other species. Oak forests have declined due to land use changes, industrial forestry favoring conifers, and browsing by wild ungulates. Oak grows best on deep, fertile soils but can survive on a range of sites, supporting high biodiversity, and have cultural, aesthetic, and recreational value. The temperate climate is expected to change, and the increased temperature and rainfall potentially will favor oak over other species. Historically, high sowing rates and low-cost labor contributed to successful oak establishment; planting has since become the main method. Interest in seeding is returning, but predation and germination risks make it less certain than planting. Site preparation and high seeding density can help mitigate losses where heavy acorn predation by rodents is expected. Competition from other vegetation requires intensive mechanical site preparation and periodic cleaning operations. Seeding is more successful on abandoned farmland with less rodent habitat and where agricultural practices can be used for site preparation and maintenance. Expensive fencing is required for protection from browsing, especially in the first 10 years. Restoration success requires regular assessment and management, with lower oak seedling densities acceptable if other species are present. Lack of experience among managers is a barrier; more information and communication about successful practices are needed.

Keywords

Quercus, direct seeding, seed predation, ungulate browsing, afforestation, manager inexperience

Contents

1 The forest

Forests in Sweden are mostly coniferous forests of the boreal region. The two main tree species are Norway spruce (*Picea abies* L.) and Scots pine (*Pinus sylvestris* L.). However, there are two oak (*Quercus* spp. L.) species from the section Quercus found in southern Sweden, pedunculate oak (*Q. robur* L.) and sessile oak (*Q. petraea* (Matt.) Liebl.), and they overlap considerably in range, forest types, and ecological characteristics (Gömöry et al. 2001). Oak-dominated forests in the region have gradually declined over recent millennia due to several factors such as changed land use, introduction of industrial forestry that has promoted conifers over broadleaves, and more recently, over-browsing by wildlife (Petersson et al. 2019). Today, oaks are distributed south of Limes Norrlandicus, the northern limit of the temperate forest zone in Sweden, i.e., ca. 100 km north of the capital city Stockholm (Sjörs 1999) (Figure 1). Oak stands are mainly found on fertile sites with deep soils, often in the transition between farmland and coniferous forest, but also on nutrient-poor sites in coastal areas (Löf et al. 2016).

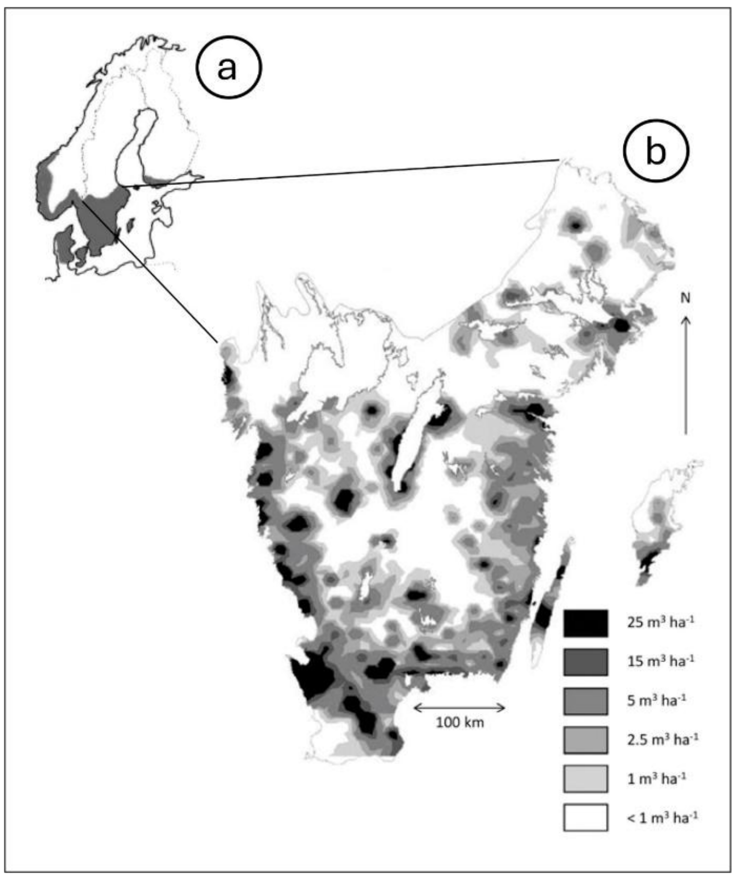

Figure 1. Distribution of standing volume of oak in southern Sweden south of 'Limes Norrlandicus,' the northern limit of the temperate forest zone. The Nordic countries with distribution of oaks (grey) (a), and southern Sweden with standing volumes of oaks (b). The data is derived from the Swedish University of Agricultural Sciences and the Swedish National Forest Inventory (SLU-SNFI) during the years 1993–1997.

In the southern region, oak is a minor part of the total standing volume, i.e., 4%, which is dominated by Norway spruce, Scots pine, and birch (*Betula* spp. L.) (SLU 2020).

The oaks occur in pure stands for timber production but also in mixtures with other tree species such as Norway spruce, Scots pine, and birch (Drössler et al. 2012). Many of these pure oak or oak-rich mixed forests derive from past land uses such as wood pastures, coppice, or abandoned agricultural lands. Small private forest owners own most oak-dominated forests, and although the owners focus on timber production, oak wood production often plays a minor role in the economy of these forest owners.

The climate of southern Sweden is temperate, corresponding to Central European weather conditions. There are four distinct seasons and mild temperatures throughout the year. Extreme southern Sweden corresponds to Köppen Cfb oceanic, while the more northerly portion of the region corresponds to Dfb warm-summer continental climate. Mean annual precipitation decreases from about 1000 mm in the west to 600 mm in the east, and the mean temperature ranges from −3 °C in January to 16 °C in July (reference time span 1961–1990) (SMHI 2025). The climate that favors oak is warm springs and summers with relatively high annual precipitation. Cold winters may kill acorns that are not well protected in the forest floor, and late spring frost may damage flowers and young seedlings, thus limiting the regeneration process (Löf et al. 2019). For the region, temperatures are expected to increase by 2–6 °C by the end of this century and the warming will be more pronounced in winter than in summer. It is thought that total annual rainfall will increase over southern Sweden by about 10%, but simulations suggest that summer drought with high temperatures may become common in the eastern parts. Additionally, the weather is expected to become more extreme, with heavier rainfall events, longer dry periods, and more frequent gales with high wind speed (Aldea et al. 2024). Generally, the projected shifts in climate are considered to favor oak relative to other tree species (Dyderski et al. 2017).

Oak stands are found on a wide range of soils and trees survive well on both relatively moist and dry sites (Carbonnier 1975). The best growth of oak is found on deep soils with a clay content, i.e., on land most often used for agriculture. Here, pure oak stands can produce up to 6 m^3 ha^{-1} yr^{-1}. At the end of the rotation period, such stands may have a basal area of about 20 m^2 ha^{-1} and an average tree height of 30 m. On poorer and drier soils, growth and tree density is much lower, perhaps around 1 m^3 ha^{-1} yr^{-1} volume with basal areas of ca. 10 m^2 ha^{-1}. Such stands are often found along the coasts of southern Sweden (Figure 1).

Oak trees and forests are associated with high biodiversity and a range of aesthetic, symbolic, religious, recreational, and historical values, and are generally favored by the public. Oak-dominated forests support high biodiversity (Mölder et al. 2019). This is because they are generally more open than other forests, are allowed to age, and the trees themselves produce important micro-habitats. For example, bark that is sun-exposed is important for a wide range of insects, and older oaks have coarse bark, branches in various stages of decay, retain a lot of dead wood, and may have many cavities (Ranius et al. 2008, Paltto et al. 2011). Policies relating to oak forests have primarily concentrated on protecting the most biodiversity rich sites and protecting remaining stands from conversion to other land uses, primarily conifer-dominated forestry (Löf et al. 2016). To compensate forest owners for the associated silvicultural costs of managing oak forests, regeneration and early stand management of oak stands are subsidized.

Nowadays there is much interest in using oak forests and mixed broadleaved forests as an adaptation strategy to climate change. Although the volume production of oak forests is lower compared to coniferous forests, it is considered to be more ecologically and economically stable. Oak forests rarely blow down during gales, the species are considered to be more drought-tolerant relative to many other tree species, and they are tolerant to various insects (Bolte et al. 2009). In addition, at the end of the rotation period, the value of oak timber can be very high. Policies to promote oak forests are developed by European Union and national authorities, and many forest owners are interested. However, there is little information, guidelines, or resources available for managers who want to restore oak forests.

2 History of southern Swedish forests and forest degradation

Land use history in Europe has led to the fact that only ca. 0.2% of the European temperate broadleaved forests remain in a near-natural condition (Hannah et al. 1995). As such, the temperate broadleaved forest represents one of the most degraded ecosystems in the world. More such forests remain as managed forests and in southern Sweden approximately 6% of the total standing volume consists of temperate broadleaved tree species with oaks as the dominant species (Anonymous 2024). Temperate broadleaved forests covered much larger areas historically than they do today (Björse and Bradshaw 1998; Lindbladh et al. 2014). Scandinavia was covered with ice until about 10,000 years ago, and about 6,000 years ago temperate deciduous forest dominated the region. Thereafter, the share of temperate broadleaved forest declined due to a combination of factors such as a less favorable climate, colonization by other tree species, and cultivation of the best soils. Over the last 200–300 years, temperate broadleaved forests were overexploited for timber, grazing, and firewood, and much land was cleared for farming (Spiecker et al. 2004). At the same time, industrialization created a need for more timber, which promoted reforestation and afforestation with faster growing conifers such as Norway spruce and Scots pine. During the last 80 years or so, Norway spruce has been the preferred species of industrial forestry because of its rapid growth, its easy establishment and management, and its unpalatability to browsing animals (Lodin et al. 2017). Therefore, forests in the region are dominated by these two conifer tree species, and forest industry is heavily dependent on this timber resource. In this forest landscape, dominated by conifer plantations and agricultural fields, oak-dominated forests occur as small fragments, and most of these forests are managed for timber production.

3 Mitigating impacts for seeding

Browsing by wild ungulates (Family Cervidae), such as moose (*Alces alces*), roe deer (*Capreolus capreolus*), red deer (*Cervus elaphus*) and fallow deer (*Dama dama*), are the biggest challenge to regenerating oak in southern Sweden. Ungulate populations have increased during the last 50 years due to changes in game management, changes in land use, and milder winters (Petersson et al. 2019). Expensive fences, costing up to 20 Euros m^{-1}, are needed to protect seedlings, drastically increasing the total cost for regeneration (Figure 2). Fencing to prevent wild ungulate browsing should be maintained during the first 10 years following establishment. Thereafter, oak seedlings most often have reached a browsing free height, and the fencing can be removed, which is also a cost. Most often, 2-meter-tall, metal-wire fencing is needed to protect regeneration areas from moose, but lower cost fences can be used if moose are not present at the site. Some research is ongoing to investigate low-cost alternatives to tall metal-wire fencing, for example, wooden fences, slash fences, or ecological solutions like establishment of thorny plants or use of repellents. However, clear results and direction for implementation are yet to develop.

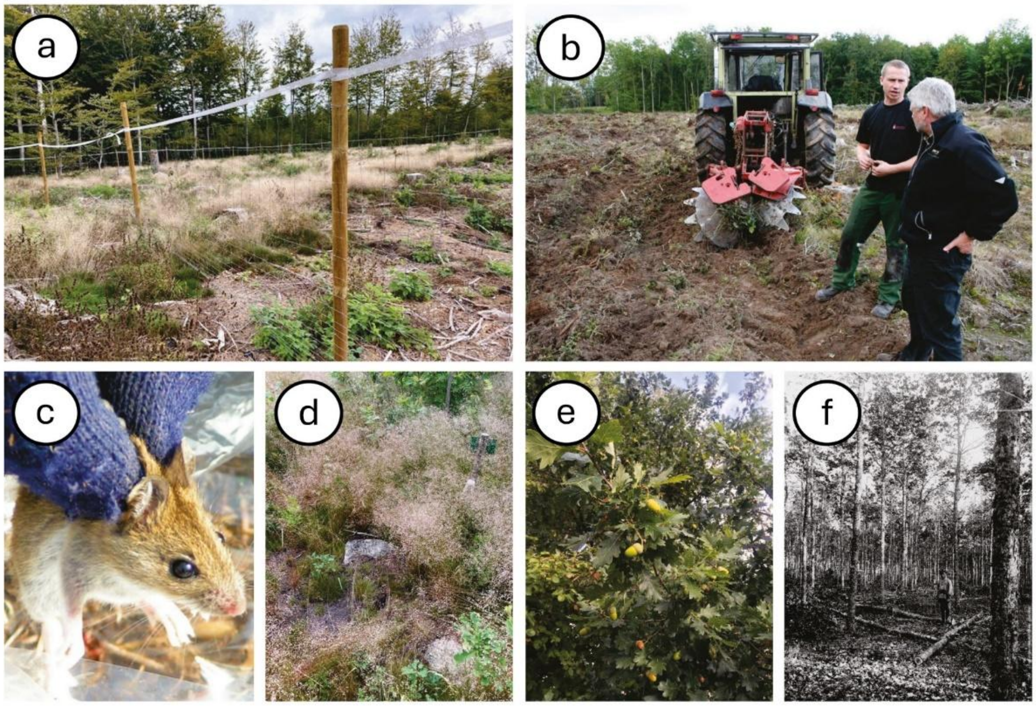

Figure 2. (a) Fenced area to regenerate oak through seeding in southern Sweden, (b) mechanical site preparation to prepare a site for seeding acorns, (c) a captured wood-mouse (*Apodemus sylvaticus*) within a seeded area, (d) newly established oak seedlings with competing vegetation, (e) *Q. robur* acorns still attached to tree in autumn, and (f) an oak forest (57 years old) established with seeding in 1867 in southern Sweden. (Photo credits: (a) Magnus Löf, (b) Palle Madsen, (c) Maria Birkedal, (d) Magnus Löf, (e) Gunnar Schotte, (f) Forest Library SLU, Umeå, Sweden.).

Because of their high energy and nutrient content, acorns are highly attractive to a wide range of animals including insects, birds, and mammals such as rodents (Order Rodentia) and wild boar (*Sus scrofa*) (Löf et al. 2019). Acorns shed to the forest floor are rapidly removed by animals and either consumed or hoarded for later consumption. Animals that cache or disperse acorns for later consumption may act as both predators of seed and facilitators of natural regeneration, because some acorns are dispersed to micro-sites suitable for seedling establishment. This is the case for many forest rodents including mice, rats (Family Muridae), and squirrels (Family Sciuridae). Rodents can remove acorns from forest restoration sites within weeks of sowing, even if acorns are buried (Villalobos et al. 2020) (Figure 2). Granivorous rodents use their sensitive olfactory sense to locate buried seeds. Rodents prefer sites with some tree cover or where other protection is available, e.g., stones, bushes, stumps, grasses, etc. It is therefore difficult to establish oak by seeding on forest land where rodent habitats are available. Several potential tools for protection from small mammals have been tested; these include seed and seedling tubes, mechanical site preparation, and repellants made from predator odors (Löf et al. 2019). None of these have so far been shown to work on a practical scale and it has proven very costly to protect individually sown seeds. However, when seeding larger clearcuts (> 1 ha) substantial amounts of acorns will escape predation, especially if little ground vegetation is present at the site (Villalobos et al. 2020). Thus, the size and proper site preparation of the regeneration area should be considered. In such cases, the local rodent population cannot remove all acorns if seeding density is sufficient—acorns that are not predated may produce a satisfactory number of seedlings to regenerate the area.

Seeding acorns works well on abandoned farmland where small rodent habitat is lacking. At such sites (abandoned farmland with no vegetation), the seeding operation can be performed with agricultural machines and equipment, herbicides are allowed for controlling competing vegetation, and therefore costs can be drastically reduced to approximately one-third of the costs of planting seedlings (Madsen and Löf 2005).

An additional challenge to newly established oak seedlings, on both forest and former farmland sites, is competition from other vegetation. Oaks are normally regenerated on fertile sites that support rapid colonization and growth of herbaceous and woody plants, and small seedlings can be outcompeted if this vegetation is not controlled (Löf et al. 2019). To control vegetation, intensive mechanical site preparation is needed on forest land, i.e. mounding or inverted mechanical site preparation. This will facilitate oak seedling establishment and growth during the first few years after sowing. Thereafter, cleaning operations are needed periodically during years 5 through 15 to release seedlings and saplings from competing vegetation. In southern Sweden, herbicides are not allowed to be used on forested land, so it is not an alternative during seeding operations at such sites.

4 Seed procurement and preparation

Acorns are collected on the ground manually by contractors in good seed years (mast years) (Löf et al. 2019). Sometimes nets can be laid out on the ground to simplify the process. There are a few nurseries in the region that buy and store acorns to cultivate oak seedlings. However, native seed or plant material is not always available. Seeds and seedlings are often purchased from dealers and nurseries in Denmark, Germany, Norway, Poland, and the Netherlands. Acorns are stored in high humidity and at temperatures around 0 °C. At the nurseries, seed quality is tested according to international standards, and acorns are treated with heat and fungicides to prevent fungal attacks. Some skilled foresters collect acorns themselves and store them over winter in jute bags that are lowered into streams of running water. This method was much more common in the past, when oak sowing was also more common.

5 Plant establishment

Acorn seeding is normally done in the spring, but sometimes acorns are sown in the fall. Fall sowing has the advantage that acorns do not need to be stored over winter, but the disadvantage that they are exposed to a longer period of predation by small rodents. On agricultural land, the seeding rate is about 70 kg ha^{-1} with a spacing of 2 m x 1 m (Löf M and Møller-Madsen 1997). The site should be harrowed before sowing to improve seedbed conditions for germination. After sowing, harrowing should be done again to cover the seed with soil. The site should then be treated with herbicides to minimize the establishment of competing vegetation.

On forest land, relatively large clearings (> 1 ha) can be sown successfully if intensive mechanical site preparation is used and sowing density is high (> 100 kg ha^{-1} acorns, spacing 1 m x 1 m) (Löf and Madsen 1998). In the 19th century, when oak seeding was more common, very high sowing densities were used (up to 10 acorns at each seeding spot) and poisons were used to protect the seed from small rodents (Carbonnier 1975). There are few successful examples of sowing acorns when a dense tree layer occupies the site, e.g., sowing under dense shelterwoods or in small gaps. In such locations, small rodents thrive and seek shelter in the surrounding vegetation. Thus, the acorns need to be protected for a few months until the young oak seedlings are established. Some research has been conducted to find cost-effective countermeasures, such as effective repellents against seed predation by small rodents (Villalobos et al. 2023). However, so far, no practical solution has been identified. Chemicals that counteract predation and simultaneously do not harm small rodents are very expensive, and formulations that sustain repellent properties over time in natural environments have yet to be developed.

6 Successful seeding

From the early 1800s until the 1930s, virtually all oak forests established in southern Sweden were seeded. The success was partly due to the fact that foresters and landowners used very high sowing rates. Practices associated with seeding operations (seed collection and sowing) were done with a low-paid labor force typical of that time. After the 1930s, seedling planting became the main tool for afforestation and reforestation as fast-growing conifers were in demand and dominated as planting material.

Nowadays, interest in oak seeding has returned. More broadleaved forests are needed to adapt forests in Sweden to the changing climate and to protect biodiversity (Bolte et al. 2009). We need to learn to establish oak stands through seeding again and develop the practice into an effective regeneration option. Some guidelines for this are described in this article.

Sowing is currently a more uncertain method than planting. This is mostly due to predation on sown acorns but there are also risks during seed germination. Too, acorns can freeze or dry out before they germinate. Any failures need to be detected in time. Assessment of restoration success needs to be done twice a year during the first two years after establishment. Once seedlings are established, management during the first ten years should focus on reducing competition with other vegetation. If there is too much competing vegetation already established on the site at time of regeneration, seeding should not be used. Planting large bare-root seedlings is a better option because they compete better with surrounding vegetation. Motor-manual pre-commercial thinning should be done at least two to three times during the first ten years. Afterwards, fencing can be removed.

A limitation to achieving a larger area of restored oak forest through sowing is the lack of experience and competence of forest managers with this practice. Today, only a few managers know how to implement seeding practices for oak establishment. Therefore, although sowing has great potential to be developed in the long term, planting will dominate in the near future. In general, there is a need for more information and communication about successful oak restoration with seeding. Most often, a seedling density of 2,000 to 10,000 oak seedlings ha^{-1} is considered a successful operation. However, when establishing oak regeneration, seedling densities do not need to be so high. Area between oaks may be occupied by other tree species that add value to the stand and can be harvested at a profit. At the end of the rotation period of the oak (100–150 years in southern Sweden), there are typically only about 50–70 oaks ha^{-1}. If intensive management of the young oaks or groups of young oaks can be implemented and the surrounding natural vegetation managed more intensively during the beginning of the rotation, cost-effective alternatives to planting can be developed.

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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.

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