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Best practice prescriptions for propagating and establishing pedunculate oak *(Quercus robur)* for timber production

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Introduction

Two native oak (*Quercus*) species occur in Britain, sessile oak (Quercus petraea) and pedunculate oak (*Quercus robur*). Pendunculate oak is considered to be a pioneer tree species, while sessile oak is a later successional species (Ducousso and Bordacs 2004). Both our native oaks belong to the white oak group of the genus *Quercus* and section *Quercus* (Denk *et al*. 2017). The natural distribution of each species has been obfuscated by considerable planting over many centuries (Savill 2019). Furthermore, while there are barriers, they hybridise and are closely related enough genetically for some to suggest they are ecotypes of the same species (Jurkšienė *et al*. 2020). In Great Britain, oak is an important genus, representing 16% of forest cover (Forest Research 2018) and it is valued for its strong and durable timber (Savill 2019) but is also an important tree ecologically, supporting over 400 species of leaf-eating insects (Southwood *et al*. 1984, in Savill 2019).

There are, however, constraints to growing oak in Britain, most notably the economic and physical damage caused by grey squirrel (*Sciurus carolinensis*) and deer (*Cervidae*), and the slow rate of growth of between Yield Class 4 and 6 m3 ha^{-1} y^{-1} on most sites (Savill 2019). Control of grey squirrel is a priority, and several new initiatives may have potential (Forestry Commission 2019). There are also opportunities to increase growth rates and reduce rotations, for example, through the system involving final tree selection and release used in France and described by Lemaire (2014), or by principles of free growth, described in Kerr (1996). There is also potential to considerably increase the timber quality of oak and other broadleaves grown in Britain. A comparison of sawlog volume produced per hectare of broadleaved woodland in France, Germany and Britain showed that Germany produces 15 times as much sawlog and French six times as much per hectare compared with Britain (Taylor 2019). This wasted potential of broadleaved woodland in Britain has acted as a catalyst for this review of establishment of oak. The aim of this document is to provide best-practice prescriptions for seed selection, planting stock propagation and selection, and tree establishment..

Silvics of pedunculate oak

The two native British oaks have similar ecological requirements but there are differences as summarised in Table 1.

Acorn production in pedunculate oak varies considerably between years, with large quantities being produced every 2-4 years (Aldhous *et al*. 1994). These events are known as mast years and influence wood production, tree health (with growth being reduced after mast year), natural regeneration (Nussbaumer *et al*. 2021) and create a constraint to seed supply. Mason *et al*. (1999) describe both the native oak species as being intermediate in their light requirements. However, Lemaire (2014) and Ellenberg and Leuschner (2010) describe pedunculate oak as being more light demanding than sessile oak.

Also, pedunculate oak tolerates wider climatic conditions that sessile oak (Annighofer *et al*. 2015) and although it is more likely to suffer dieback during droughts, conversely it is better adapted to exploiting waterlogged soils (Lemaire 2014, Annighofer *et al*. 2015). In terms of soil nutrition, Lemaire (2014) describes pendunculate oak as being more demanding of soil nutrients (Table 1) but in the Ecological Site Classification (Ray 1995) and in Evans (1984), they are described as having identical requirements. Shake, an important defect in the timber of oaks, is linked to soil conditions, with attributes that limit root development and nutrient uptake being the most important factors (Price 2015).

Pedunculate oak exhibits periodic shoot growth during the growing season with episodes of growth interspersed by episodes of rest. This periodicity of growth does not occur in the roots which continue to grow continually through the growing season (Harmer 1990). Oaks are known to have strong apical dominance (inhibition of lateral branching on the current year's growth) but weak apical control (inhibition of a lateral branch by shoots above it). Thus, older stems and branches are likely to form lateral branches, but the leader is not (Harmer 1990, Brown *et al*. 1967). As such, regular loss of the leading shoot is likely to produce a tree of poor form.

Table 1 Silvicultural characteristics of pedunculate and sessile oak.

	Pedunculate oak	**Sessile oak**
Light requirements	Intermediate [6] but more light demanding [1,4]	Intermediate [6], less light demanding [1,4]
Soil fertility	High fertility [2], more demanding [1]	Moderately high fertility [2], less demanding [1]
Soil depth	Deep rooting >60cm and preferably >1m [2]	Evans [2] gives the same requirements as pedunculate oak but Lemaire [1] states that it tolerates poorer and shallower soils.
Moisture requirements - acorn	Tolerates some surface water (more tolerant that *Quercus rubra* and *Quercus palustris* [5])	Intolerant of wet conditions [1]
Moisture requirements - seedling	Will not survive even short periods of drought [1]	Can tolerate varying soil moisture conditions [1]
Moisture requirements - adult	Suffers badly from seasonal droughts [1]	More drought tolerant [1]
	Can tolerate permanently wet conditions [1,2] and sea water [2]	Cannot or less tolerate permanently wet conditions [1,2]

1 Lemaire, (2014), 2 Evans (1984), 3 Savill (2013), 4 Ellenberg and Leuschner (2010), 5 Colin-Belgrand et al *(1991), 6 Mason* et al *(1999).*

Seed & nursery

Recommended seed sources

UK qualified seed orchard material should be available for pedunculate oak in 2035, which will be the recommended material for planting from southern England to central Scotland (Future Trees Trust 2022). This will not only produce trees of better form but also those with high resilience to environmental change as the population being genetically diverse being derived from plus trees selected from across England.

Hubert (2005) reviewed the results from oak provenance trials in the UK and until seed orchard material becomes available, his recommendations should be followed. In order of preference he advised the following:

1 Use selected material for British seed stands.

2 Use selected material from near continental seed stands.

3 Use source identified British material.

4 Do not use material from a far continental climate. It is better to delay planting or select a different species.

Furthermore, larger vessel size in earlywood is a predisposing factor to shake and this is related to late flushing and early leaf fall (Price 2015) so seed from populations that exhibit these traits should be avoided. Hubert (2005) noted opportunities to increase growth by moving populations north and to improve frost resistance by moving them south. While Hubert's (2005) findings were based on trials where sessile oak was the predominant species, the findings are likely to be valid for pedunculate oak. A review of results from relevant trials and physiological experiments can be found in Whittet *et al*. (2019).

Seed selection, storage and pre-treatment

Studies from North America have shown that acorn size is strongly related to high percent germination, rapid shoot emergence, high survival and rapid early growth (Johnson *et al*. 2009). For European oaks, this would also appear to be the case, and the effect of acorn size on increasing tree growth would appear to be long lasting, the benefit only diminishing by age 14 years (Johnsson 1952). For pedunculate oak specifically, acorn size may influence germination and seedling performance. A study from Serbia showed larger acorns exhibited higher rates of germination and seedlings of lower shoot:root ratios, but this was based on a relatively small number of acorns (Devetaković, *et al*. 2019). Work undertaken in Turkey on sessile oak recommended using larger acorns combined with undercutting to produce larger, more vigorous bare-rooted planting stock (Tilki *et al*. 2009).

Gosling (2007) describes oak as having a recalcitrant seed with shallow dormancy. This limits the period that it can be stored while maintaining viability; the germination percentage of the seed will normally decline from 90% to 50% over the 10–24 weeks between collection in autumn (October/November) to the sowing in spring (March/April).

Oak characteristically produces large quantities of seed during periodic mast years (Szuba *et al*. 2022). This, combined with the recalcitrant nature of its acorns, complicates meeting demand by customers from nurseries. To maintain viability, while minimising growth of fungi, seed should be stored in conditions of low temperature (–3ºC to +5ºC), which slows the rate of deterioration, and high humidity to reduce desiccation and allow respiration and gas exchange (Gosling 2007). Szuba *et al*. (2022) support these findings, stating that acorns can be stored for 1.5 - 2 years at –3ºC and a moisture content of 40%. Moisture content when stored is also important for subsequent successful germination. In a study by Ozbingol and O'Reilly (2005), soaking acorns and increasing their moisture content above 40% prior to storing at –3ºC enhanced germination rate and germination percentage. A later study which examined seedling performance in addition to germination, showed that drying and soaking yielded higher germination, higher seedling yields and better-quality seedlings, when compared with dried acorns. It also compared germination of untreated acorns and soaking and drying improved germination before and after storage (Doody and O'Reilly 2008). Gosling (2002) provides detailed prescriptions for acorn, handing, transport and storage.

Raising planting stock and timing of planting

Initial shoot growth of oak seedlings is slow with much of its resources devoted to developing a long taproot after germination in autumn and by the end of the first growing season this can be 0.5 m long (Johnson *et al*. 2009). The tap root is mainly for storing carbohydrates and has a covering that is largely impermeable to water.

In contrast the lateral roots' prime function is water and nutrient uptake (Johnson *et al*. 2009). Root morphology is important to the quality of planting stock of oak and is a crucial factor in successful establishment. Those seedlings with a greater number of first order lateral roots normally perform better in the field (e.g. Kormanik *et al*. 2002). Planting stock of oak for forestry purposes is either bare-rooted or cell grown. The choice of methods used to raise oak planting stock is important as they affect root architecture, taproot starch reserves and root:shoot ratios (Zadworny *et al*. 2020). The activities involved in raising quality bare-rooted oak are described in Table 2.

Undercutting has two benefits: (1) reducing the overall tap root length, facilitating planting, (2) stimulating lateral root development on the tap root, above the cut (Andersen 2004). Undercutting was found to increase

Table 2. Nursery operations

Stage	Operation	Practice
Seed handling	Seed Storage	Best to sow acorns soon after collection (Gosling 2007, Johnson *et al* 2009).
Seedbed	Pre-treatment	Acorns are treated at 42°C for a few hours to kill fungi (Summerfield pers com 2022). Soaking and drying has been shown to improve germination success and better-quality seedlings (Doodie and O'Reilly 2008). Increasing the moisture content to 40% or above by soaking and then storing at low temperatures (-3°C) increased germination and rate of germination compared with acorns that had not been soaked (Ozbingol and O'Reilly 2005).
	Seed bed treatment	To control weed growth, the seed bed is treated with residual herbicide (Summerfield pers. comm. 2022).
	Sowing time	Acorns should be sown as soon as possible after collection (Gosling 2007).
	Sowing density	Acorns are sown at 250 seeds m-2 and seed bed density is important. Good quality oak cannot be grown in dense conditions as space allows development of robust root systems (Morgan 1999). High seedling densities therefore produce small seedlings with lessened growth potential (Johnson *et al* 2009). A single undercutting operation after the first growth flush encourages a more fibrous lateral root system and a more balanced root:shoot ratio (Morgan 1999).
	Protection	On germination the seedlings are treated for mites and powdery mildew, they are covered with 2.5-4 cm of soil (Morgan 19999) and with fleece (Summerfield pers. comm, 2022) or a mulch (Johnson *et al* 2009) to prevent frost damage. Mouse (*Mus* spp.) predation can be a problem for large seeds like acorns.
	Nutrition	Once germinated a nitrogen top dressing is applied at 150kg N ha^{-1} (Summerfield pers. comm, 2022). Increasing application of nitrogen, up to 160 kg ha^{-1} increased seedling growth and density (O'Reilly *et al* 2008).
Transplant bed	Nutrition	Growth is most rapid with a fertilization rate between 0.5-1.5g N $seedling^{-1}$, which allows bare-rooted planting stock to be produced within a year (Schmall *et al* 2011).
	Time of lining out	Deciduous hardwoods like oak are lined out before conifers. This is February to March in England and Wales and as late as mid-May in Scotland. Frosts are generally over by this time and soil is beginning to warm up above the 5-6°C threshold for root growth. The seedlings should be lifted and transplanted as quickly as possible. If this is not practical, the seedlings need to be safely stored.
	Planting density	Growing space has a strong influence of seedling size but particularly seedling basal area (Table 6.6).
Transplant treatment	Undercutting	When the buds have hardened, around October/November of the first year in the transplant bed they are undercut at about 15cm depth using a 200mm x 10mm blade. This encourages development of fibrous roots and limits the length of the tap root. Oak does not generally develop long lateral roots, so side pruning is rarely necessary.
	Lifting	Lifting is normally at the end of the first (1+1) or second growing season (1+2) after autumn when the seedlings are dormant (Morgan 1999). Timing is shown in Figure 1.
	Root pruning	Roots are pruned to ensure they are of a standard length which facilitates planting.

lateral root size, with undercut seedlings producing lateral roots mostly >1mm diameter with relatively few branches and a small decrease in fine roots, while the lateral roots of untreated seedlings were mostly <1mm diameter (Harmer and Walder 1994). A trial was established with bare-rooted stock undercut once, undercut twice and not undercut, in competitive situation (no weeding, watering or fertilising) and conventional conditions (weeding, watering and fertilising). In general, seedlings in the undercut once treatment had a significantly higher dry weight than the uncut seedlings two growing seasons after planting (Andersen 2004). In the competitive conditions, first year growth of seedlings was focused on roots rather than shoots (Andersen 2004). The effect of weed competition may be similar to severe drought as the response of *Q. petraea* and *Q. robur* to severe drought is a change in the partitioning of biomass from shoots to roots, whereas the main response to mild drought is osmotic adjustment (Thomas and Gausling 2000).

On drier sites, undercutting may not be beneficial. A study from Poland showed that container grown or bare-rooted stock that retained a significant taproot exhibited characteristics most likely to favour their growth and survival on drought-prone sites (Zadworny *et al*. 2020). Mucha *et al*. (2018) found that undercutting changes the root:shoot ratio, favouring shoot growth which has implications for growth and survival on drier sites. On more benign sites, if bare-rooted stock is used then it should be undercut. Timing of undercutting has been shown to have an effect on growth of planting stock of pendunculate oak with undercutting in July giving the best results (Table 3) (Tilki *et al*. 2009). Taproots act as starch reserves when the tree is unable to photosynthesise due to moisture stress

To ensure planting stock has a healthy root:shoot ratio, the size specifications for bare-rooted oak and other broadleaves is described in Table 4, and for cell-grown broadleaves in Table 5.

Table 4. Minimum root collar diameters (mm) for different heights of bare-rooted planting stock (birch = Betula *spp., beech =* Fagus sylvatica*, ash =* Fraxinus excelsior*, gean =* Prunus avium *and lime =* Tilia *spp.) (Morgan 1999) except second entry for oak (Aldhous and Mason 1994).*

Species	**Height range (cm)**				
	20	**30**	**40**	**50**	**60**
birch	3	4	4.5	5.5	6.5
beech	4	5	6	7.5	9
oak/ash/ gean/lime	5	6.5	8	9.5	11

Table 5. Minimum root collar diameter (mm) and cell volume (cc) for cell-grown broadleaved trees (Morgan 1999).

Attribute	**Height range (cm)**			
	10-20	**20-40**	**40-60**	**60-90**
Minimum root collar diameter (mm)	4	4	6	8
Minimum cell volume (cc)	50	100	150	200

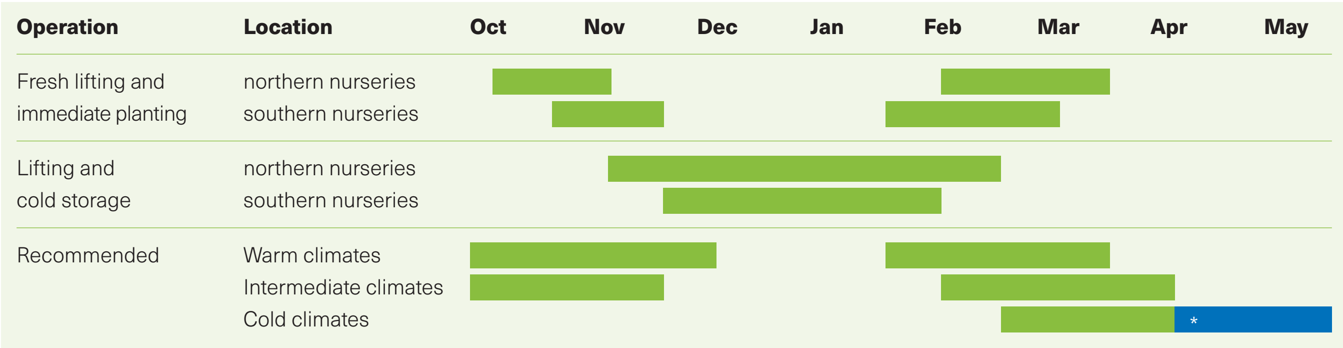
The timing for lifting, storage and planting of bare-rooted stock is shown in Figure 1. Using cell-grown stock extends the planting season as survival is better when planted out of season (Kerr 1994).

Nutrition is known to be important for seedling growth. A trial examining the effect of fertiliser application on oak seedling growth after one growing season in the seed bed showed that increasing fertiliser from 40 kg N ha^{-1} up to 160kg N ha^{-1} significantly increased seedling density (higher survival), seedling height and proportion of seedlings greater than 40cm (O'Reilly *et al*. 2008). Normally producing bare-rooted stock of oak takes 2 years (1+1) but using exponential nutrient loading they can be produced within one year (Schmal *et al*. 2011).

Table 3. Treatment on pedunculate oak and effect on seedling root dry weight, shoot dry weight, number of fine lateral roots and number of coarse lateral roots (Tilki et al *2009).*

Treatment	**Root dry weight (g)**	**Shoot dry weight (g)**	**Number of fine lateral roots**	**Number of coarse lateral roots**
Uncut control	6.7^a	2.8^b	9.8^b	3.8^c
June	5.2^b	2.4^b	11.4^a	6.3^b
July	6.9^a	3.4^a	11.2^a	5.0^b
June & July	4.2^c	1.7^c	7.2^c	3.5^c

Figure 1. Timing of nursery and planting operations in relation to location: northern nurseries - Onset of dormancy is early and release from dormancy is late, southern nurseries - Onset of dormancy is late and release from dormancy is early. Cold climates – northern England, Scottish and Welsh mountains (Accumulated temperature <1050 degree days), Intermediate climates - northern England, Scottish and Welsh uplands (Accumulated temperature 1050 - 1350 degree days), warm climates – Most of England and Wales and coastal areas of southern Scotland (Accumulated temperature >1350 degree days) (Morgan 1999).



** only cold stored material should be planted in this period.*

Where possible, oak planting stock should be planted as quickly as possible. A study was conducted by Cabral and O'Reilly (2009) where bare-rooted planting stock was stored at 15°C for 0, 15 and 31 days and the field performance assessed two years after planting. This was to investigate the effect on growth of an increasing delay between lifting and planting. Warm storage negatively affected growth of *Q. robur* seedlings, especially when stored for the longer period of 31 days. Bare-rooted trees should be planted as quickly as possible after lifting.

Cell-grown stock of oak is also used in Britain, however, published details on propagation could not be found. Snowden (pers. comm.) describes the approach used at Cheviot Trees. Acorns are not intentionally soaked and are normally sown soon after collection in autumn, preferably before Christmas. If they have been stored, or if germination is poor, they will be mixed with growing media and left to germinate. The rate of germination is influenced by manipulating light and ambient temperature. At Cheviot Trees, a peat-free medium with slow-release fertiliser, designed to release nutrients in spring, is used for cells.

Research from elsewhere on pedunculate oak has shown that container size and shape have a strong influence on biomass allocation. Air pruning in deep and narrow containers retarded growth but in wider and deeper containers there was not this effect (Marrioti *et al*. 2015). A method has been developed in the USA called the RPM process. This involves sowing selected, large acorns in a shallow tray with a fertilised growing media and mesh bottom to produce seedlings with a limited taproot but extensive fibrous, lateral root system. These are then transferred into large pots, between 11 and 19 litres in volume and bottomless to allow air pruning of the roots. This produces a robust seedling with high survival and better diameter growth than bare-rooted stock (Dey *et al*. 2004).

Mycorrhizal inoculation of container media has an influence on the seedlings. Dixon *et al*. (1984) inoculated container grown pedunculate oak seedlings with the following ectomycorrhizal fungal associates *Pisolithus tinctorius, Suillus granulatus, Cenococcum geophilum, Thelephora terrestris,* and *Suillus luteus*. They found that seedlings with abundant mycorrhizal networks exhibited larger root and shoot dry weights and had a larger leaf area.

Establishment

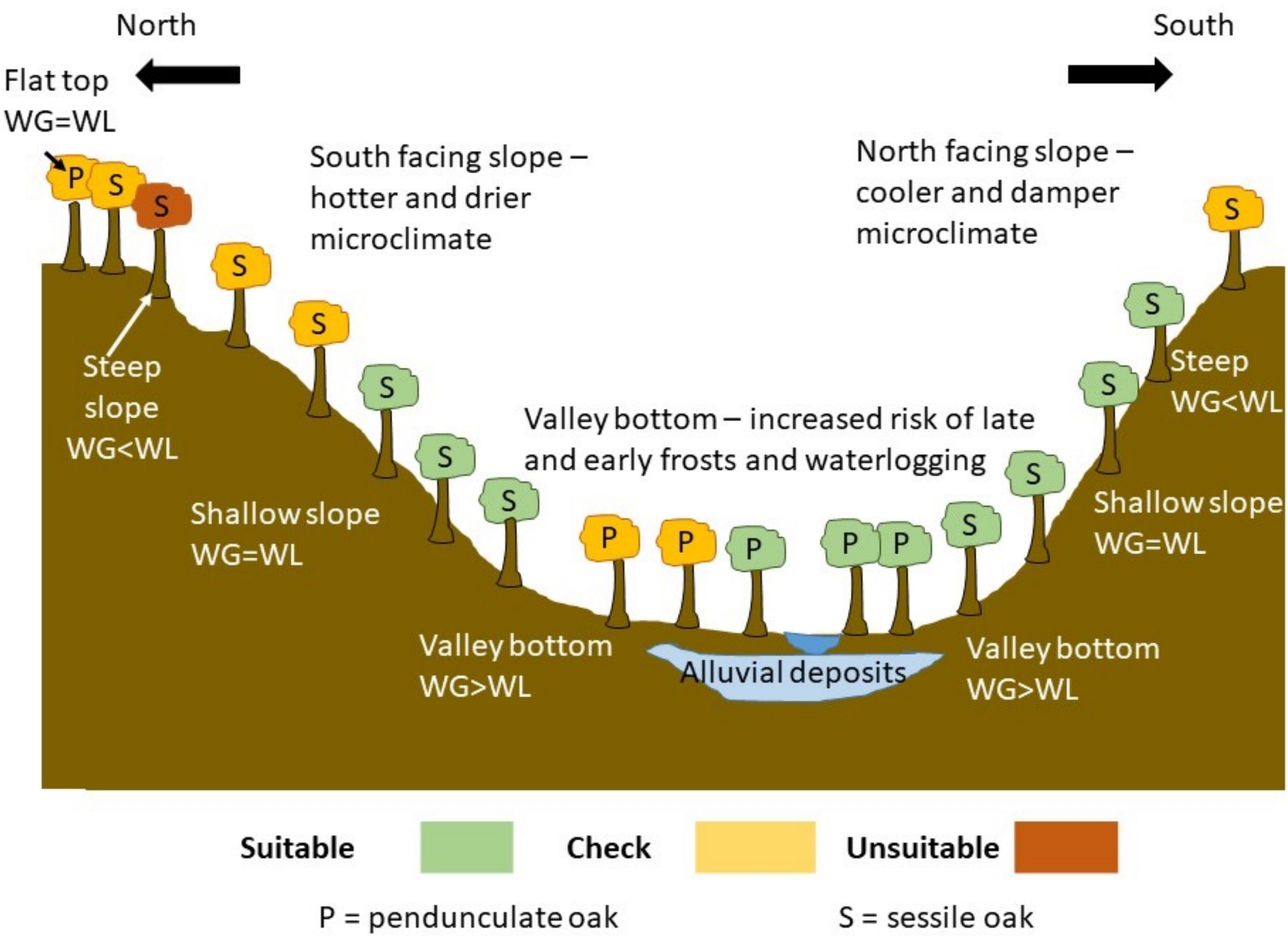
Site selection

Due to the importance of soil moisture conditions on oak productivity (Lemaire 2014) and probability of occurrence of shake (Price 2015), topography has an important influence on growing quality oak. Site classification systems developed for oak in the USA combine topography with other factors such as soil texture, aspect and soil depth (Gysel and Arend 1953, in Johnson *et al*. 2009; Johnson and Rogers 1982, in Johnson *et al*. 2009). In general, lighter soils, slopes, northern aspects and shallow soils reduced productivity of oak. The influence of topography on site suitability for sessile oak was also described in Lemaire (2014) where topography that facilitates the accumulation of soil moisture (i.e. water gained>water lost) are to be favoured for planting (provided waterlogging does not occur). There are differences in site requirements between the two native oaks and it is recommended that planting of pedunculate oak should favour moist, nutrient rich sites while drier sites with poorer soils should be planted with sessile oak (Lemaire 2014, Levy *et al*. 1992). These findings are summarised in Figure 2, which shows suitability of different microsites for pedunculate and sessile oak.

Shake is an important factor impacting the value of oak timber and Price (2015) in a summary of evidence on environmental factors predisposing oak to shake recommended the following: while brown earth sites are generally favoured for planting oak, those with low levels of calcium, high levels of calcium, low pH or with a gravelly texture are likely to encourage shake; in contrast, clay soils, deep soils and those with constant soil moisture conditions reduce the probability of shake.

The long rotations of oak means that climate change will have a strong impact on any trees planted.

Figure 2. The influence of aspect, topography and soil water conditions on suitability of pedunculate and sessile oak. For soil water conditions, WL is water lost and WG is water gained (created from two diagrams in Lemaire 2014).



Predictions of productivity under climate change have been produced by Petr *et al*. (2014) for pedunculate oak. They have divided GB into the uplands and the lowlands, and productivity is predicted to increase across the uplands and also in northern areas of the lowlands. In southern areas, it is predicted that there will be a considerable decline in productivity due to increased moisture deficits.

Planting material selection

There are two broad types of planting stock for oak, bare-rooted and containerised. Kerr (1994), in a trial of different container grown seedlings and bare-rooted stock, found container-grown material to exhibit better growth (Table 6) and survival, and particularly to perform better when plant handling had been poor and when the trees were planted outside the normal planting period. A study of planting on two farm woodland sites in England compared cell-grown and bare-rooted stock and found that 1-year cell-grown material demonstrated better growth and survival than 2-year bare-root undercut material of a similar size (Burgess *et al*. 1996). Survival and growth of 1-year-old undercut bare-rooted stock was better than the 2-year-old seedlings but not as good as cell-grown material, particularly when planted late in September (Burgess *et al*. 1996). A study by Kerr (1994) using sessile oak on two sites, comparing stock grown in three different types of container with bare-rooted stock, found that cell-grown stock survived better when poorly handled but that there was better survival only in some cell-grown stock when the material was carefully handled. Height growth was significantly better at both sites using cell-grown stock. The general recommendation of using containerised stock, rather than bare-rooted stock in more drier site conditions and when handling is poor is supported by Grossnickle and El-Kassaby (2016), although they note that once established growth is similar.

Table 6. Growth (cm) in one growing season of sessile oak using bare-rooted stock and stock raised in different containers (Kerr 1994).

Type of container	Growth (cm) Affpuddle site	Bossington site
Rootrainer	6.0	6.2
Rigipot	5.8	4.5
Japanese Paper Pot 515	6.3	6.4
Bare-rooted	3.2	1.9

However, Kerr (1994) notes that results from trials of different types of planting stock often cover only a few types of site and planting stock, and so advocates the development of a seedling quality index to define and quantify those seedling attributes that lead to successful establishment rather than focusing on container versus bare-root. Where weed competition is the primary limiting factor on a site, then larger planting stock is favoured. In general, larger planting stock performs better (Grossnickle and El-Kassaby 2016). Guidelines for southern USA for white oak recommend using trees between 45 and 60 cm tall based on more rapid height growth and being more robust when under browsing pressure and competition from vegetation (Clack *et al*. 2022).

Nutrition

Pedunculate and sessile oak tolerate a very wide range of soil conditions (Savill 2019) but have different nutritional requirements with the former being considered more demanding than the latter (Evans 1984, Lemaire 2014). However, a glasshouse study conducted by Newnham and Carlisle (1969) demonstrated that the situation was more complex and pedunculate oak was found to have a higher phosphorous requirement (41 ppm vs 12 ppm) but lower nitrogen requirement (43 ppm vs 86 ppm) for optimal seedling growth. The study identified that oak would be deficient in phosphorous but there would be almost sufficient soil nitrogen in the soils of Silurian slates and Carboniferous limestones of north Lancashire (Newnham and Carlisle 1969). A pot experiment in Austria using sessile oak on a poor, acidic soil and a rich, calcareous soil found that an input of NPK fertiliser increased growth, but particularly on the poorer soil (Berger and Glatzel 2001). There is a general presumption that the use of chemical inputs will be reduced over time (Forestry Commission 2017). A review by Miller (1986) concluded that, at the rates of application used in forestry, problems arising from leaching were unlikely and that enhanced growth normally lasted five to ten years. This would accelerate establishment and reduce maintenance costs while improving growth rates. However, nutrient inputs can reduce mycorrhizal infection in pedunculate oak (Newton and Pigott 1991).

Mycorrhizae may offer an alternative to fertilisers in improving tree nutrition by increasing water and nutrient uptake. However, it is difficult to choose appropriate fungus species for artificial inoculation as there is no universal best mycorrhiza species, and improvement in growth only occurred in half the studies reviewed by Holusa *et al*. (2015). An experiment where recently-planted and older stands (9-10 years old) of pedunculate oak were inoculated with mycorrhizae yielded largely inconclusive results, although there was more active mycorrhizae on the roots of inoculated trees, and in all the older stands the stem diameter of inoculated trees was larger (Holusa *et al*. 2015). In Poland, Leski *et al*. (2010) found significantly different mycorrhizal associations on oak in different nurseries while in north America, a study on *Quercus garryana* showed that mycorrhizal species were completely different and less diverse on seedlings in the nursery compared with trees in natural stands (Southworth *et al*. 2009). Mycorrhizae also affected growth in the nursery, with mycorrhizal abundance, particularly of *Laccaria mycorrhizas*, a significant predictor of seedling height (Southworth *et al*. 2009). A study of mycorrhizae of pedunculate oak and silver birch grown in pots and in the field, showed that seedling mass was positively related to the number of mycorrhizal tips on the roots but not the overall extent of mycorrhizal colonisation, other than when low phosphate levels limited growth (Newton 1991).

Controlling competing vegetation

While oaks large seedlings' reserves make them While oaks large seedlings' reserves make them relatively competitive with grasses, *Deschampsia flexuosa* and *Holcus mollis* are considered strong competitors and require control (Savill 2019). Davies (1985), in a trial in south-east England on a grass and clover site, demonstrated the importance of herbicide application in ensuring good growth of oak, although survival was not significantly different from those without weed control. However, an approach used in southern USA is to plant oak on mounds with the ground between colonised by weeds or planted with a cover grass (*Agrostis gigantea*). Those planted in the grass treatment had much more rapid growth in the first three years and also less rabbit damage (Dey *et al*. 2004).

In a study of oak growth across four German states, a crucial factor reducing oak growth was competition from other woody perennials (Molder at al 2019). This was supported by a field trial in southern Sweden which found the competition from other trees to have a much greater effect on growth and survival of *Q. robur* than herbaceous (mainly grasses) weeds. The competition from both herbaceous and woody weeds also improved stem form but this was most marked when it was woody vegetation (Jensen and Lof 2017). Competition from woody vegetation therefore creates a trade-off between survival and oak stem quality that can be manipulated to meet management objectives (Jensen and Lof 2017, Liziniewicz *et al*. 2016). A study in Sweden of competition from woody vegetation on pedunculate oak confirmed that the main effect was through aboveground rather than belowground competition. However, in a drought year it is likely that the importance of belowground competition will increase (Jensen *et al*. 2011).

Protection

Oak is slow growing, growing 10-20cm per year for the first 5 to 8 years (Evans 1984) and thus require a relatively long period of tending and management of weed competition. Improving early growth will yield benefits in terms of cost of establishment. When oak is young, growth occurs in stages. There is an initial growth stage that may only last a week and then the seedling enters a resting phase. In favourable environments such as nursery beds this resting stage can last 2 to 4 weeks but in harsher field conditions it can be longer and if seedlings are under water stress or in low light then they may remain in this resting phase for the whole growing season (Johnson *et al*. 2009).

Growing conditions can be ameliorated through the use of tree shelters. Potter (1991) described oak as being a genus where use of tree shelters will enhance height growth by over 100% compared with mesh guards. Other studies (Liović, *et al*. 2019, Marriotti *et al*. 2015, Valkonen 2008, Davies 1985) have confirmed this positive response in height growth, although on drier sites the lower root:shoot ratios of tubed trees may make shelters unsuitable (Marriotti *et al*. 2015). There is growing concern about the use and disposal of traditional plastic shelters, but research is being conducted on biodegradable alternatives (MacKinnon 2020). Combing tree shelters with weeding enhances their effect, although weeding had a stronger influence than the adoption of shelters (Davies 1985).

Cultivation

Practical recommendations for cultivation of different soil types in the UK have been presented in Haufe (2020) and these recommendations apply to oak. A comparison of mounding, herbicide, combined mounding and herbicide and a control on sites in Sweden with a high water table demonstrated the benefits of mounding when planting oak (Bolte and Lof 2010). Mounding, compared with repeated herbicide application, was more beneficial through the development in seedlings of a more extensive roots system and greater lateral root growth (Bolte and Lof

Table 7. The effect of different sized spot herbicide treatments and tree shelters on the establishment of oak transplants after two years (Davies 1985)

Attribute		**Weeded spot diameter (m)**			
		0	**0.25**	**0.5**	**1**
Height growth (cm)	Without shelter	22	25	28	25
	With shelter	51	64	69	78
Basal area growth (mm2)	Without shelter	23	35	39	54
	With shelter	13	31	34	42
Volume index	Without shelter	31	42	45	60
	With shelter	34	67	75	100
Survival (%)*	Without shelter	97	100	98	95
	With shelter	91	92	97	95

2010). The authors' only proviso was to be careful of nutrient losses from the mineralisation of humus and its effect on ground water eutrophication. The positive effects of cultivation on soil temperature are also likely to be important as the rate of soil warming is key to oak establishment and early growth (Larson 1970, in Johnson *et al*. 2009).

Planting patterns and use of mixed species stands

To grow quality oak for timber, the weak apical control exhibited by oaks (Harmer 1999) must be addressed to ensure light branching and good form. There are several approaches to achieve this, but they all involve placing the trees under competition to promote upward growth of a main stem and reduce branching. Prescriptions for oak and hornbeam and oak and beech mixes can be found in the Forest Development Types flashcards produced by Haufe *et al*. (2021).

Grant funding in England requires planting of broadleaves at a normal stocking density of 1,100 stems ha^{-1} for broadleaves and will not pay for stocking densities of more than 2,500 stems ha^{-1}, although applications will be considered for planting at higher densities (Forestry Commission 2022). The Forest Research Forest Development Types for oak recommend planting at higher densities than those funded by grants (Haufe *et al*. 2021) and in Germany oak is normally planted at 5,000 stems ha^{-1}. There are potential approaches to planting where overall stocking densities are relatively low but which still encourage high levels of competition between individual trees. Such approaches involve cluster planting of oak, a technique first suggested in the UK by Anderson (1930). Saha *et al*. (2002) describes two cluster approaches to establishment of oak for quality timber. These were group planting and nest planting, with natural regeneration of other tree species being desirable between the clusters. In the nest design, clumps of 21 oaks are planted at 0.25 m spacing, the distance between the central tree of each clump being 7 m, the final crop spacing. For the group plantings, there were three variants, all with a 1 m spacing between the trees within groups and a distance of 10 m between centre of the groups. The high levels of competition reduced survival and suppressed growth, particularly of diameter in the nest plantings when compared with the German practice of planting at 2 m x 1 m spacing (5,000 stems ha^{-1}). In contrast the group planting did not compromise growth and improved stem quality.

Planting oak in a mix with other species offers opportunities to improve stem quality and volume production. In parts of Germany, it is traditional to grow high quality oak in an intimate mix of beech (*Fagus sylvatica*) (von Lupke 1998), creating an overstorey of oak and an understorey of beech. The heavy shade from the beech supresses the growth of epicormics on the oak, improving the timber quality. In the USA, a mixed stand of red oak (*Quercus rubra*), red maple (*Acer rubrum*) and hemlock (*Tsuga canadensis*) produced higher biomass than any of the species in monoculture (Kelty 1989).

For more conventional planting, formative pruning of selected stems should be practiced when the trees reach 1.2-1.6 m in height (Bulfin and Radford 1998a). This should be focused on the better stems, as on trees with poor apical dominance intensive pruning was required to maintain a favourable stem form and this reduced diameter growth (Bulfin and Radford 1998b).

Conclusions

Pedunculate oak is a major broadleaved tree species in GB and in Europe, and is important for timber and the conservation of biodiversity. This study reviewed easily accessible English language texts on propagation and establishment of pedunculate oak and provides some best-practice prescriptions. It has also identified areas where additional investigation would be worthwhile.

Recommendations

The recommendations arising from this review can be divided into seed and nursery and establishment.

Seed and nursery

- When seed from GB seed orchards for pedunculate oak becomes available it should be used. Until then seed from selected GB stands should be used.
- In years when there is a good supply of acorns, that larger acorns are used to produce planting stock.
- Increasing the moisture content to 40% or above by soaking and then storing at low temperatures (-3°C) increased germination and rate of germination compared with acorns that had not been soaked (Ozbingol and O'Reilly 2005).
- Soaking and drying improves germination and seedling quality.
- Fertiliser application to around 160kg/ha N of seed beds will improve growth and yield of larger plants in oak. (O'Reilly..)

Establishment

- Planting stock should be planted as quickly as possible after delivery to the planting site but no longer than 15 days after delivery.
- On dry sites planting stock with a large taproot should be favoured (large cell-grown?).
- On wet sites, mounding has been shown to be an effective cultivation method in Sweden.
- Cell-grown stock is more resilient to poor handling and allows greater flexibility of handing but there is not strong evidence for better field performance across a range of sites.
- Glasshouse and pot-based experiments show that fertiliser application will increase growth on rich soils and more so on poorer, acidic soils. On nutritionally poor sites fertiliser application will increase growth for the first five to ten years, accelerating establishment and reducing rotation.
- Tree shelters should be used as they significantly enhance growth in all sites, except possibly on drier sites due to a lower root:shoot ratio.
- Oak seedlings have relatively large reserves but still suffer from weed competition. This is particularly the case for competition from woody weeds which considerably reduce growth but conversely may improve form.

Further research

There are also some areas that have been identified for future research:

There is some evidence that larger acorns produce more resilient planting stock and this should be tested.

The increased root:shoot ration of trees in shelters should be investigated and the impact on growth and survival of dry sites determined.

Even on relatively fertile soils there appears to be opportunities to enhance growth through fertiliser application. Also, there appears to be a trade-off in mycorrhizal abundance and benefit with increasing soil fertility.

There are opportunities, through collaboration between nurseries, to develop a single nursery protocol for oak which incorporates best-practice from a number of nurseries.

There has been limited research on the benefits of different pot sizes and shapes on field survival and growth.

The benefits of using cover crops or cultivation instead of herbicides should be investigated for oak.

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