Forestry Commission

Research Report

Shake in oak: an evidence review

Forest Research

Forestry Commission

Research Report

Shake in oak: an evidence review

Andrew Price

Forestry Commission: Edinburgh

This publication is also available on our website at: www.forestry.gov.uk/publications.

First published by the Forestry Commission in 2015.

ISBN: 978-0-85538-925-3

Price, Andrew (2015).
Shake in oak: an evidence review.
Forestry Commission Research Report
Forestry Commission, Edinburgh. i–iv + 1–28pp.

Keywords: oak; oak shake; Quercus spp; silviculture; timber quality.

FCRP024/FC(STUDIO9)/WWW/APR15

Enquiries relating to this publication should be addressed to:

Forestry Commission
Silvan House
231 Corstorphine Road
Edinburgh EH12 7AT

0300 067 5000
publications@forestry.gsi.gov.uk

The author can be contacted at:

Forest Research
Mortimer Forest Office
Whitcliffe
Ludlow
Shropshire SY8 2HD

0300 067 6980
andrew.price@forestry.gsi.gov.uk

Contents

Introduction 1
Henman's model of shake development in oak 2

Predispositions 3
Large earlywood vessel diameter 3
Wounding 5
  Wounding and barrier zone formation 5
  Wounding and bacterial wetwood formation 6
Abrupt changes in ring width 7

Triggers 9
Physiological stresses 9
  Soil nutrition, type and pH 9
  Soil texture, stone content and moisture content 10
  Substrate and lithology 14
  Available rooting depth 17
Mechanical stresses (external forces) 18
  Wind 18
  Severe cold temperature 18
  Steep slope 20
Growth/support stresses (internal forces) 20

Summary of evidence 22

References 26

Introduction

Shake is the phenomenon of internal, longitudinal splitting of the wood in a growing tree. It occurs in either an annular pattern as ring shake or radially as star shake and is only possible to detect definitively once a tree is felled. Oaks can be affected by either or by both types, although star shakes occur more frequently than ring shakes. Figure 1 shows both types with characteristic staining. This report addresses shake in native oak species, that is pedunculate (*Quercus robur*) and sessile oak (*Quercus petraea*). Some of the factors reviewed (e.g. large stem diameter, sudden release of growth, low calcium availability) are also believed to initiate shake in sweet chestnut (*Castanea sativa*).

Logs that may otherwise be suitable for higher value decorative or structural use may be so degraded by shake that they are fit only for fencing or even firewood. Logs may be devalued by up to 80% of their full potential value. Shake therefore represents a very major economic defect to the UK growing and processing sectors, especially since there is a persistent shortage of larger, better quality domestic hardwood sawlogs. Henman (1986a) determined financial losses to be as high as 80% on individual logs. Mather and Savill (1994) estimated some 21% of British high forest oak trees to be affected, representing an annual loss of 57000 to 79000 tonnes of sawlogs at a cost of £3–8 million to British growers (with further impacts on the UK trade deficit since the costs of imported replacement hardwood were estimated at £9–13 million per year). A more recent study of a highly shake-prone site (73% of trees affected) indicated a likely financial loss of about 21% on the overall sale parcel (Price and Munro, 2011).

Current UK forest policy (Scottish Executive, 2006; Welsh Assembly Government, 2009; Defra, 2013) is to significantly increase forest cover and to improve the economic potential of broadleaved woodland, much of which is of low financial value. The level of investment required to establish oak for better quality timber production is relatively high and rotations are normally very long (up to 150 years). A better understanding of the factors influencing shake will enable

Figure 1 Star and ring shakes present in the same log (the unstained cracks are natural 'checks' caused by the drying-out processes).

future investment to be targeted at lower risk sites for new planting and may help identify existing stands of higher risk oak in order that future resources may be concentrated on lower risk crops or the early removal of vulnerable individuals during thinnings.

A brief summary of the available information on shake in oak is presented in Forestry Commission Research Information Note No. 218 (Henman and Denne, 1992). A considerably wider evidence base now exists regarding the factors that contribute to shake development and, in particular, their interrelationship. The purpose of this report is to collate this evidence, assess its relative strength and provide, where possible, recommendations for managers. While this report has sought to draw upon as wide an evidence base as possible, the majority of hard evidence from the UK originates from key studies by Savill (1986), Savill and Mather (1990) and Henman (1991).

Henman's model of shake development in oak

The model of predispositions and triggers developed by Henman (1991) very usefully summarises the key factors believed to influence shake in oak and their interrelationship (Table 1). This research suggests that there is no single cause of shake, but that both a predisposition and a trigger must exist in order for shake to occur (i.e. a predisposed tree will not develop shake in the absence of a trigger and triggering factors will not lead to shake unless a tree is already predisposed). Subsequent research has not presented evidence to alter this model, although recent studies by Forest Research indicate that a further predisposing factor, the presence and distribution of tension wood, may have an influence and this is currently under investigation. It is also proposed that distinguishing between inherited and acquired predispositions may be useful. Suggested amendments to Henman's model are indicated by red text in the table.

In the next two sections, which deal respectively with predispositions and triggers, the general outline of Table 1 is followed though not under exactly the same headings or in the same order. The evidence is then summarised in the tables in the final section.

Table 1 Model of the various factors leading to the occurrence of shake in oak (after Henman, 1991)*.

Predisposition (an in-built structural weakness, or an otherwise weakened or stressed area of wood)	Trigger (an aggravating stress)
Inherited i.e. due to genetic variations in wood structure and chemistry including: • Large earlywood vessel diameter • Natural variation in growth stress levels and wood strength	Growth/support stress (internal) Mechanical stress (external) including: • Wind • Severe cold • Steep slope
Acquired i.e. due to wood structure being modified by environmental influences including: • Cambial injury • Abrupt change in ring width due to drought, defoliation or removal of competition • Degradation of wood by anaerobic bacteria associated with wetwood around barrier zones • Increased earlywood vessel diameter due to site or cultural factors • Significant areas of tension wood generated in vulnerable areas of the main stem	External factors causing physiological stresses including: • Substrate/lithology • Soil texture • Soil stone content • Available rooting depth • Soil pH • Soil moisture availability

* Preliminary findings from an ongoing study by the author indicate that a wide variation in the speed of acoustic transmission (linked to wood stiffness) around a tree's circumference may identify an imbalance of growth stresses that could be associated with shake. A further study is currently testing this hypothesis.

Predispositions

Large earlywood vessel diameter

Large earlywood vessel diameter (inherited or acquired predisposition) is known to be highly correlated with shake. Larger vessels increase transpiration rates and may reduce drought tolerance and lead to stress in root systems. The characteristic is highly heritable so genotype may determine resistance or susceptibility to the defect, but there is also strong evidence that environmental factors may influence vessel diameter during early season growth. Vessel diameter has already been used in selection criteria for parent trees in the current Future Trees Trust oak breeding programme*. Larger vessel diameter is also known to be correlated to later bud flushing and to earlier leaf-fall, enabling the early identification of vulnerable trees within stands (Savill and Mather, 1990; Mather, Kanowski and Savill, 1992).

Scientific evidence

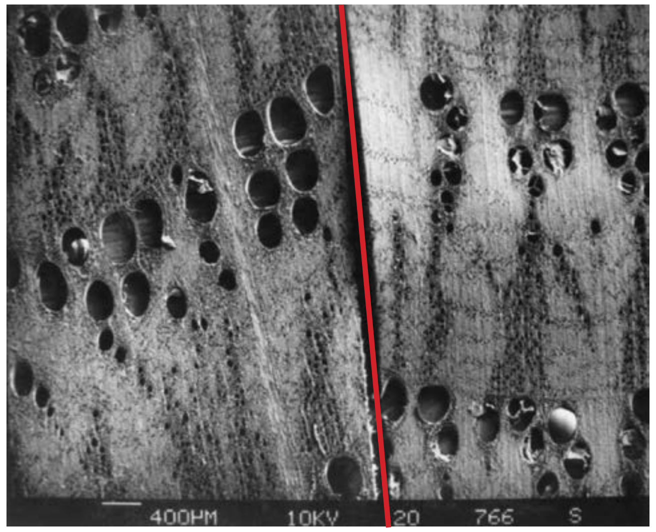
Xylem growth and lignification are broken down into two periods: earlywood (formed in springtime) and latewood (formed during summer). Vascular components are discernible in visible patterns. Broadleaf species are generally either ring-porous, with larger vessels produced in early season growth and concentrated in the outer sapwood, or diffuse-porous, with smaller vessels produced across the full growing season and functioning throughout the sapwood. Deciduous oak species are ring-porous. The wood structure in oak is complex with up to five rows of large and solitary earlywood vessels around the growth ring and an abrupt transition to latewood. Latewood vessels are much narrower and are relatively insignificant in terms of conductivity. The British native oak species (and sweet chestnut) have the largest known earlywood vessels of any temperate tree species (Savill, 1986).

Large earlywood vessels increase the efficiency of water conduction but at the risk of cavitation (collapse) during periods of drought when internal pressure can become very low. Close proximity to the cambium makes them vulnerable to external damage and to the subsequent entry of pathogens (Zimmermann, 1983). Individuals with larger vessels also suffer moisture stress earlier than those with narrow vessels (Mather, Kanowski and Savill, 1992), which may explain their relatively early onset of leaf senescence (see below).

* See www.futuretrees.org/our-work/oak

When comparing shaken and unshaken trees from a number of known shake-prone sites, Savill (1986) found that earlywood vessel diameter was highly correlated to shake, indicating that trees with substantially larger vessels (Figure 2) have a significantly greater predisposition. (All of the shaken trees in this study suffered star shake, with about half also having some ring shake: although the relative influence of vessel diameter was not discussed the predominance of star shake may indicate a stronger association with vessel diameter.) Large cells are known to initiate local cell wall fractures, which may then extend leading to more substantial defects; the phenomenon is described by Savill as similar to bone, coral or concrete with large pores being more prone to fracture. Cinotti (1987; cited in Henman, 1991) also found that oak trees suffering from frost crack, an associated phenomenon (see section on severe cold temperature, page 18), had significantly larger earlywood vessels. Savill and Mather (1990) later defined the risk threshold as having a mean earlywood vessel diameter of greater than 160 µm, both for species and for individual trees. A recent study (Price and Savill, 2013) investigated whether acoustic devices might be used to detect large vessel diameters in standing trees but found there to be no relationship between vessel diameter and acoustic velocity.

Figure 2 Electron microscope photographs showing two horizontal sections of oak timber with very large earlywood vessels (left) and smaller vessels (right).



Reproduced with the kind permission of Peter Savill (Future Trees Trust).

Kanowski, Mather and Savill (1991) demonstrated that vessel diameter in both sessile and pedunculate oak is under strong, additive genetic control and is therefore highly heritable.

Savill and Kanowski (1993) and Savill *et al*. (1993) proposed that European oak improvement programmes could use this to help address the problem of shake. In the late 1990s the Future Trees Trust (at that time the British and Irish Hardwoods Improvement Programme) identified 200 oak trees on the basis of superior form (straightness, branching, vigour, timber quality) and selected only those with narrower vessels as suitable parent trees. Offspring have now been used to establish eight breeding seedling orchards.*

There is strong evidence, however, that vessel size is not exclusively under genetic control and that environmental or site factors are also important. Additional work by Denne and Henman (1990) compared nine-year-old oak trees (both sessile and pedunculate) grown in tree shelters with unsheltered trees at seed origin trials and found that those grown in shelters had significantly larger vessels during their first three growing seasons after planting. A further study by Henman (1991), based on comparison of individual trees from a wide range of stands, including known shake-prone and shake-free sites, found no widespread correlation between vessel diameter and the presence of shake. Those from shake-prone sites, however, had appreciably larger mean vessel diameters (along with wider growth rings, larger wood rays and a lower proportion of earlywood) than those grown on shake-free sites, irrespective of whether shakes were present.

Both sessile and pedunculate oak are believed to have the ability to effectively 'record' water availability during early spring since the cells walls of that year's production are loosened according to the flow of growth regulators (auxins) and are stretched by the turgor pressure of available water over a period of a few weeks, with the final vessel diameter being determined at the onset of lignification (García-Gonzales and Eckstein, 2003). Noting this apparent variability in the vessel diameter, dendroclimatic studies of Spanish-grown pedunculate oak by the same researchers found a strong positive correlation between vessel diameter and rainfall during the period of February to April, with more frequent 'rain events' leading to larger diameters and vice versa. Warmer temperatures were negatively correlated with vessel size. Subsequent studies by Fonti and García-Gonzales (2008) confirmed that mean vessel diameters in oak show a stronger response to climate (i.e. spring precipitation and temperature) than ring width variables, so may in fact be a better proxy for climate reconstructions.

With regard to shake, the site factors leading to consistently larger vessel diameters must therefore be associated with increased springtime moisture availability rather than free drainage; this may therefore offer some evidence to support the traditional associations of shake with waterlogged sites. An early study by Henman (1986a) of nine highly shake-prone sites included just three on sandy soils but six on silty soils, and the potential significance of silty soils as a shake risk in relation to moisture retention is discussed, if inconclusively, in the section on soil texture, stone content and moisture content, page 10. Although other studies indicate that ring shake is strongly associated with free drainage and that star shake is more likely to arise from large vessel diameter, it is evident that further research is required to identify the causes of a particular site being prone specifically to star shake.

Vessel diameter is also known to be highly correlated with the timing of the onset of flushing and leaf-fall. Studies by Savill and Mather (1990) and Mather, Kanowski and Savill (1992) found that individuals with the largest earlywood vessel diameter within a stand will flush relatively late and drop their leaves earlier than those with smaller vessels.

Does the evidence enable recommendations for management?

Although the researchers do not appear to have actively made a distinction with regard to shake type, there are indications that large vessel diameter has greater significance as a cause of star shake than of ring shake. Assessment of vessel diameter requires microscopic analysis and, while this is of great benefit to breeding programmes, it is unlikely to be of practical use for owners or buyers or standing crops. However, since it has been shown that within a population those trees with the largest vessels flush relatively late it may be possible, if resources permit, to identify vulnerable individuals so that they might be removed early in the crop rotation.

Mention should also be made of the potential influence of tree shelters, since there are indications that mean vessel diameter in oak may be increased during the first three growing seasons (Denne and Henman, 1990) and it is known that small ring shakes near to the pith can initiate larger star shakes in mature trees. The benefits of using tree shelters are so great however, in terms of protection and rapid establishment, that on the basis of available evidence their use should in no way be discouraged. Nevertheless, this will be an interesting subject for future study, once the trees established in shelters begin to reach economic maturity.

* Improved seed orchards are initially established as breeding seedling orchards. Young trees are assessed for growth, vigour and form during the first two decades. Poorer specimens are then removed to leave the very best individuals to produce seed by breeding with each other.

Wounding

Wounding and barrier zone formation

External wounding (acquired predisposition) in the main stem or basal area of a tree is known to be highly correlated with ring shake (Shigo, 1972). Any damage that penetrates the bark and damages the cambium exposing the wood can result in the subsequent formation of weak-walled cells and may also lead to physical separation of the damaged wood from the overlying new tissue. Kubler (1983) noted that a wounded tree 'does not really heal, it only covers the wound with wood and bark callus tissue that grows over from its edges'.

The speed and effectiveness of the healing process depends on other site factors and is also known to be highly important in determining shake risk. Poor soil nutrition or other aggravating factors may prevent a wound from healing quickly and effectively (see section on soil nutrition, type and pH, page 9). This is likely to result in a point of significantly greater structural weakness than would a well-healed wound.

Scientific evidence

Trees growing in plantation are subject to intentional or unintended damage by pruning, harvesting machinery and the skidding of logs, animals, fire or wind. Very low temperatures may lead to localised cell mortality, sometimes with subsequent canker formation (Henman, 1991).

The term barrier zone was coined by Shigo and Larson (1969; cited in Henman, 1991) to describe the mass of undifferentiated tissue with large, thin-walled cells that develops over a wound to protect the subsequent healthy growth from any infected tissue (also described by Shigo as being like an 'internal bark'). These layers of cells are chemically strong against fungal attack but are mechanically weak. The strength of response to fungal invasion, the extent of barrier zone formation and the potential for ring shake are thought to be chemically determined (Henman, 1986a, citing Shigo and Marx, 1977), which may in turn be influenced by inherited genetic factors (Henman, 1991). The overlay of new cells on damaged, dead or infected tissue results in separation of the wound surface and any callus tissue. The barrier zone, although initially localised, may later form the basis of a more extensive separation within the wood, especially if subject to significant external or internal stresses. This is sometimes referred to as 'traumatic' shake (Shigo, 1972; Kubler, 1983).

Wounding also causes localised changes to the wood properties of any subsequent regrowth, resulting in further structural disparity and weakness once later growth normalises. Studies in the USA have focused on the North American deciduous species of red oak (*Quercus rubra*) and white oak (*Quercus alba*). McGinnes, Change and Wu (1971) found shake zones associated with external injuries to be characterised by higher contents of extractives, lignin and methoxyl, lower holocellulose content and a lower degree of holocellulose polymerisation than normal wood zones. Shigo (1972) subsequently showed that shake was extensively (but not exclusively) associated with wounding, with ring shakes usually found to result from trunk damage and star shakes typically arising from injuries at the root-collar or below.

There may be a greater risk of shake in stands of former coppice origin (i.e. in trees that have been singled from coppice stools). Shigo (1972) found that pockets of decay occur and barrier zones are formed when decayed coppice stubs have become incorporated within a new main stem. Henman (1991) found that oak trees originating from singled coppice had a high incidence of shake, even at lower stem diameters (<35 cm). The same principle may apply to trees that have been 'stumped-back' when young, that is, top growth removed (usually to 2 cm above ground) in order to promote more vigorous regrowth or to improve initial poor form.

There are also indications that tree shelters may be associated with traumatic shake. Denne and Henman (1990) felled nine-year-old oak trees and observed that a small number of them contained rot and the early indications of associated ring shake arising from stem abrasions caused by trees rubbing against the top of their shelters.

Although Henman (1991) also found a very strong association between shake and the presence of decay in individual trees it is important to note that stem wounds do not necessarily lead to shake. Chang (1972; cited in Fonti, Macchioni and Thibaut, 2002) hypothesised that ring shake may not always be determined by a unique element but as the result of several factors acting together, for example sudden and extreme temperature changes forcing open existing fractures. While studying traditionally shake-free sites, Henman (1991) found that previous cambial wounding had healed and compartmentalised very well without any subsequent barrier zone shake formation, noting that although soil nutrition is likely to be highly important (see section on soil nutrition, type and pH, page 9) the time of year that wounds are inflicted may also be significant since healing is faster and stronger when a tree is actively growing.

Does the evidence enable recommendations for management?

Options for management are likely to be limited to the prevention of injury as far as is reasonably possible (i.e. careful silviculture and protection from animal pests and fire, and avoiding damage to standing trees while felling and extracting). Corner trees at the edges of tracks and rides are likely to suffer repeated damage from the skidding of logs and should be considered as high risk (although it may be useful to retain them in order to prevent damage to other adjacent trees).

Special mention ought to be made of tree shelters, the use of which has increased greatly as a cultural technique during recent years. Although the design of shelters has improved significantly in terms of preventing stem abrasions and strangulation, attention must still be paid to careful erection and perhaps also to avoiding exposed locations since a loose or damaged shelter or a protruding stake is likely to cause significant cambial damage to a young tree.

There may also be opportunities for future tree improvement programmes (Henman, 1991) if individuals with good healing characteristics can be identified, although this trait was not selected for in the current Future Trees Trust oak breeding programme mentioned earlier.

Figure 3 Severe star shake with extensive brown staining present indicating presence of bacterial wetwood (chalky deposits are also visible in these shakes).

Wounding and bacterial wetwood formation

Wound sites (acquired predisposition), particularly at ground level or to the lower main stem, are entry points for fungi and moisture which may cause secondary degradation, compartmentalised decay and the subsequent extension of any existing separations within the wood.

Anaerobic, fermentative bacteria (*Clostridium* species; McGinnes, Chang and Wu, 1971) may also colonise wound sites both above and below ground (as may occur where roots are damaged by waterlogging or drought conditions or by root-infecting fungi), forming areas of 'wetwood' and leading to a secondary risk of splitting in the presence of external or internal forces (especially severe cold temperatures).

Scientific evidence

Shake cracks in felled trees are frequently, but not always, characterised by a dark staining around the splits (Figure 3). When affected trees are felled there is often an associated release of sour-smelling brown liquid indicating the presence of bacterial wetwood: heartwood that has been internally infused with water from an internal source (Ward and Pong, 1980). Anaerobic bacteria are known to invade damaged tissue and are better able to colonise wood where there is high natural moisture content, as is common in healthy oak trees particularly during periods of very wet weather. These bacteria may break down the middle lamella between the cell walls resulting in the separation of cells and the potential for formation of shakes (McGinnes, Phelps and Ward, 1974; cited in Henman, 1986a). Very wet and waterlogged soil, a known characteristic of shake-prone sites, will further increase sapwood moisture content (Cinotti, 1989).

Rishbeth (1982) describes the subsequent formation of tapering columns of alkaline, saturated wood following infection by non-sporing types of anaerobic bacteria. Bonding between cells in wetwood is known to be relatively weak, so radial (ring) shakes and then tangential (star) shakes may be initiated due to subsequent growth stresses within the tree or by the mechanical actions of wind or severe cold (Ward and Pong, 1980). Cracks may also be initiated or extended by high internal pressures that result from the generation of gasses (e.g. methane) by anaerobic bacteria (Rishbeth, 1982).

Any star shakes that extend through or originate from areas of infected tissue are themselves prone to become lined with wetwood and fill with bacterial fluid. Severe cold weather may freeze this fluid, forcing it outwards and causing a frost crack (see Figure 4, plus the section on severe cold temperature, page 18). The fluid is toxic to the cambium (and also to the crown if it enters the transpiration stream), which will further impede the healing process (Rishbeth, 1982).

Figure 4 Frost crack in oak.

E.L. Barnard, Florida Department of Agriculture and Consumer Services; used according to US FS creative commons licence.

Does the evidence enable recommendations for management?

New planting should be avoided in areas prone to seasonal waterlogging and/or frost hollows. Otherwise careful silviculture and management should seek to avoid injury to growing trees as far as reasonably possible. Frost cracks (fresh or healed) are a reasonably reliable indicator of wetwood and hence the likelihood (but not the certainty) of shake, so it might be prudent to identify affected trees for removal during thinning.

Abrupt changes in ring width

A sudden change in growth rate (acquired predisposition) is known to be correlated with ring shake, although this depends to a significant extent on site quality. Abrupt reductions may be caused by drought conditions during the growing season or by severe/repeated defoliation by insects. Abrupt increases may be caused by removing close competition. The physiological stresses associated with these incidents may also increase susceptibility to bacterial infection (see previous section) and consequently to a secondary risk of shake.

Scientific evidence

Ring shakes were reported by McGinnes, Chang and Wu (1971) to occur more frequently within growth rings than in between them, although both types did occur. Shakes within rings were found to arise both inside the latewood (attributed to wounding or environmental stresses) and also at the early/latewood boundary. Shakes at this interface were believed to arise due to natural differences in lignin content between the two wood types (McGinnes and Wu, 1973; cited by Henman 1991), although this research preceded the identification of large vessel diameter by Savill (1986) as a key predisposing factor (see earlier section, page 3). The boundary and the outer layer of vessels are immediately adjacent and both features will naturally represent a structural imbalance within the wood. Drought and defoliation are also known to result in weakened cell wall formation and adhesion between cells, perhaps due to the reduced availability of essential growth nutrients resulting in localised cell collapse, a narrower growth ring and a reduction in the strength of the wood (Henman, 1986a).

Growth ring effects were further studied by Henman (1986b, 1991), who observed that 'healthy' ring shakes occurred most frequently in transitional areas where there is either a sudden reduction in growth rate or when there is a return to normal growth following a series of unusually wide rings. (Ring shakes were also apparent where there was a series of uncharacteristically narrow rings.) These studies found that shakes associated with reduced growth were often common across a site, i.e. shakes occurred within the same years and in rings corresponding to known severe drought years, suggesting that drought is an important trigger. During certain years, however, the growth reduction applied only to oak species and not to local conifers indicating that severe insect defoliation, which is species-specific, was also likely to be a significant factor. Infestation by larvae of the oak leafroller moth (*Tortrix viridana*) or the winter moth (*Operophtera brumata*) may lead to complete loss of early growth foliage, with a secondary shake arising from the reduction in a tree's ability to defend itself against other pathogens (Forest Research, 2012). Oak processionary moth (*Thaumetopoea processionea)* may also become a significant factor if it becomes established in Great Britain.

An abrupt transition to wider annual rings (i.e. due to a rapid increase in growth rate following the removal of competition) was found by Henman (1991) to be especially problematic on sites where either water uptake or nutrient availability (particularly calcium) was limited, since wood strength was reduced accordingly in the wider rings. It was also found that site quality is highly important in influencing the onset of shake: richer soils with good rooting conditions mitigated the effects of an abrupt transition in ring width significantly better than those where soil structure or fertility was poorer.

It is also known that severe cold can cause unlignified cells to distort or collapse resulting in damage that can extend around the entire outer circumference of a tree's lower stem and creating a visible 'frost ring' to be formed during that year. The different wood structure between this and adjacent rings may result in a structural weakness with similarities to an abrupt change in ring width, and hence may also represent an acquired predisposition to shake (Henman, 1991).

A 'good' oak site which would be expected to produce relatively wide annual growth rings is also likely to grow a tree with a higher proportion of wood rays, due to the typically extended period of latewood growth (Zahner, 1969; cited in Henman, 1991). Wood structure will be altered accordingly and this may at least partially explain why shake still occurs on otherwise 'good' sites.

Does the evidence enable recommendations for management?

Silvicultural practices should ideally seek to maintain even growth rates as any sudden change in ring width is known to represent a potential fracture point. The careful timing and selection of thinnings is critical, particularly during early-to-mid rotations. Overstocking and excessive competition must be avoided as very narrow ring width may be especially problematic. The potential for any other environmental disturbances (particularly drought or waterlogging) that may constrain summer growth must also be considered when selecting sites or evaluating parcels of timber.

Triggers

Physiological stresses

Soil characteristics that impede rooting and inhibit the development of a healthy root system and the uptake of nutrients are believed to be the most important factors in triggering shake in oak (Henman, 1991). The series of studies by Brown (1945) and Henman (1986a, 1986b, 1991) have broadly supported the traditional assumptions and have also enabled recommendations to be refined in terms of other associated factors. Engineered soils on heavily landscaped sites or those created above non-natural substrates (e.g. mining spoil) are likely to present similar hazards in terms of rooting and stability, since these sites are often compacted or too loose in texture. There is a reasonable base of evidence on which to predict that oak crops on the following types of site will be at a higher risk of shake:

- poor soil nutrient regime (i.e. lower calcium status) or high aluminium content
- sandy, stony or gravelly soil
- shallow soil
- disturbed ground or engineered soils
- low (or very high) soil clay content
- site types or soil textures prone to seasonal waterlogging
- site types or soil textures prone to drought (particularly very free-draining soils)
- a fluctuating water table.

The following sections describe the various substrate and soil properties that will influence the likely physiological stresses on oak trees that may, in turn, trigger shake. It is not straightforward to determine all of these factors; some may require detailed local knowledge or new field surveys to be undertaken, but others such as lithology and soil data may now be collected via desk or internet-based research.

Soil nutrition, type and pH

For a tree to grow and heal effectively there must be free availability of essential soil nutrients and an absence of any toxic elements. The available evidence also indicates that these factors are highly important in determining vulnerability to shake. Good nutrition may mitigate shake risk even where a significant predisposition exists. The nutrient status of the parent lithology (see section on substrate and lithology, page 14) is also likely to be important.

The key nutrients essential for repair of damaged tissue, effective compartmentalising of wounds and also resistance to infection are known to be potassium, magnesium and calcium (calcium in particular for bonding strength between cells). If these are limited then wounds will heal more slowly and less effectively and therefore be at greater risk of later initiating a shake.

Scientific evidence

Extensive soil chemistry analyses for both shake-prone and sound sites were undertaken by Henman (1991). Soil richness and the availability of nutrients, particularly calcium, were found to be highly significant in determining whether or not a site may be shake-prone. The soils of shake-free sites typically had higher available calcium (>1.9 me/100g) than those of shake-prone sites, which frequently also had greater levels of free aluminium (perhaps due to higher soil acidity). A relatively low level of aluminium (or at least a high ratio of calcium to aluminium) was shown to be a key characteristic of shake-free sites. Aluminium in soil is known to be toxic to plants, reducing growth and also inhibiting effective healing of wounds. Henman concluded that a poor nutrient regime is of greater significance in triggering shake than moisture availability (see the next section). Several European studies have also linked very low calcium availability to the development of ring shake in sweet chestnut (Fonti, Macchioni and Thibaut, 2002).

Since plantation oak is typically restricted to mature, brown earth soils the association between soil type and shake has not been extensively researched and the main studies have focused on either soil texture (Brown, 1945; Henman, 1986b, 1991) or soil chemistry (Henman, 1991; see below). The soil groups of lowest risk for shake are likely to be the forest brown earths and (more weakly) calcareous types which are naturally richer in nutrient status. A higher shake risk can be expected on acid brown earths (of pH 4.5–6.5), where calcium tends to be lower, and on gravelly or sandy brown earths which are likely to suffer from rapid drainage and rooting restrictions. Brown rendzina soils typically occur on hard limestone and are often shallow, free-draining and stony so would be naturally risky and in any case are considered unsuitable for oak (Pyatt, Ray and Fletcher, 2001). Although not normally considered for oak in plantation, the natural characteristics of gleyed (poorly drained and typically waterlogged) and podzolic (acidic, very free-draining and often physically limiting) soils would be risky in terms of shake.

Henman (1991) noted an apparent association of shake with sandstone lithologies. Sandy soils were often found to be poorer in essential plant nutrients since they are commonly derived from a relatively nutrient-poor substrate and are more easily leached, although this does not necessarily apply to all types, especially Old Red sandstone which is known to form more fertile soils than other grades (see the section on substrate and lithology on page 14 for further discussion).

With regard to indicator vegetation, Henman (1986a) found that the species of ground flora commonly associated with shake-prone sites were bracken, heather and rhododendron, all of which naturally favour free-draining and acidic soils. Bluebell, which prefers heavy and moist soils, was found to be common on shake-free and less badly affected sites.

Does the evidence enable recommendations for management?

Broadly speaking, a lower risk of shake might be expected in woodlands with underlying silt, clay or chalk substrates (but not limestone or other strongly calcareous types), as these are likely to produce richer soils with favourable moisture retention. A higher risk can be expected on soils derived from acid, sandy or other very inert material as these are typically freer-draining with lower calcium availability. While a detailed analysis of soil nutrients is unlikely to be feasible, an indication of likely available calcium might be determined via proper identification of the lithology and soil types (see section on substrate and lithology, page 14 below). Soil pH is relatively easy to determine and can give a basic but useful indication of soil nutrient status, so is likely therefore to be a useful predictor of whether a site may be shake-prone. Acidic soils (low pH) typically have low calcium availability and are likely to be higher risk; alkaline soils (higher pH) are expected to have better free calcium availability and therefore a lower risk of shake. Indicator vegetation, where present, may also be a useful indicator of shake risk but note that it is unlikely to provide reliable information concerning the lower soil horizons (especially in the case of bluebell: Helen McKay, personal communication).

Soil texture, stone content and moisture content

Soil texture is closely associated with soil moisture content and is thought to be critical in determining shake risk (Evans, 1984; Savill, 1986). Shake-prone sites usually have lighter, free-draining, sandy soils (>20% sand content, by dry volume), which are likely to be nutrient-poor and be prone to drought. Shake-free woodlands are typically associated with heavier, well-structured clay or clay loam soils (clay content >20%), which are characterised by higher fertility and a better moisture capacity. Little hard facts exist however with regard to soil texture and only two researchers, Brown (1945) and Henman (various studies) have attempted to quantify the effects.

Stoniness is also likely to be highly important since soils with a high stone content are typically freer-draining and may be drought-prone. The development of roots and the uptake of water and nutrients may also be impeded. Where nutrient status is good, however, this is believed to be a mitigating factor, so stoniness should not be regarded in isolation, but a high stone content is always likely to represent a higher overall risk.

Scientific evidence

Brown (1945) undertook a review of (Forestry Commission) wartime felling records and found that shake was common across many different types of site, leading to the conclusion that star shake will occur almost anywhere and is likely to be under several different influences, but that only crops on sandier soils are prone to extensive ring shake. Brown's analysis (which was more arithmetic than statistical) concluded that shake of one form or another affected about one-third of stands (>100 years old) on clays or clay loams, around half of those on loams, and up to two-thirds of those on sands or sandy loams. Although Brown could show no relationship with elevation, aspect or exposure it was noted that there was an apparent trend increasing westwards across Britain, perhaps indicating an association with a 'stormier' climate.

Brown's data must be regarded with caution, since they were based on available records from many different sources, rather than a designed survey using known standards for shake recognition and diagnosis (drying checks are easy to mistake for shakes, especially in hot weather). There are also inconsistencies of presentation and in quantification of the data. However, the study highlights some interesting issues and it may be useful to attempt to represent and summarise the best of the data, given the scarcity of any subsequent studies.*

* Data entries that have been excluded from this summary are: i) entries for stands <100 years old (only partially done by Brown, who nevertheless recognised the significance of tree size in shake development), ii) entries with vague or qualitative data (e.g. 'generally sound', 'negligible', 'few'), and iii) entries (two only) with substrate descriptions that are too broad to translate into the modern lithological classifications.

Firstly, Brown's study indicates that star shakes occur much more commonly than ring shakes: this is also strongly supported by the author's own assessments and by those of Savill (1986). Brown's data also show that the ratio may differ markedly between soil textures (Table 2). Although no statistical significance can be inferred from the data as presented, it is worth noting that ring shake occurred much more frequently on the sandier soil textures.

With regard to ring shake (only), Brown's data largely support the traditional association with sandier soil textures (Table 3). Clay soils and 'loams' appear to be little or not affected.

For star shake, however, incidence is generally higher across nearly all soil types, with the exception of clay sites which are also quite low (Table 4).

The moderate-to-high frequency of star shake on loamy soils (including those with a significant clay fraction) is particularly noteworthy. The quality of the supporting soils data cannot be verified, however, and this aspect is likely to have been assessed by many different surveyors, so cannot be regarded as properly standardised. Additionally, the (strict) classification of 'loam' (i.e. quite even proportions of sand, clay and silt particles) is not included in the current Avery system (Avery, 1980).

Table 2 Relative incidence of ring shake and star shake, according to soil texture (extracted from Brown, 1945).

Soil texture, excluding sites on any superficial deposits	*n* stands assessed	*n* trees assessed	Ratio of the incidence of star:ring shakes (ranked in order of increasing incidence of ring shake)
Clay	2	65	Star shake only
'Loam'	8	269	8:1
Clay loam	26	621	3:1
Sand	8	252	3:2
Sandy loam	4	73	6:5

Note: The data pre-date the current British Avery system of soil classification (see below); star and ring shakes frequently occurred within the same study trees.

Table 3 Relationship of soil texture to incidence of ring shake (extracted from Brown, 1945).

Soil texture (predominant), excluding sites on superficial deposits	*n* stands assessed	*n* trees assessed	% of trees with ring shake
Clay	2	65	0
'Loam'	8	269	3
Clay loam	26	621	5
Sandy loam	4	73	15
Sand	8	252	15

Note: Data are ranked in order of increasing incidence and pre-date the current Avery classification system.

Table 4 Relationship of soil texture to incidence of star shake (extracted from Brown, 1945).

Soil texture (predominant), excluding sites on superficial deposits	*n* stands assessed	*n* trees assessed	% of trees with star shake
Clay	2	65	3
Sand	8	252	12
Clay loam	26	621	15
Sandy loam	4	73	19
'Loam'	8	269	27

Note: Data are ranked in order of increasing incidence and pre-date the current Avery classification system.

This lack of certainty regarding Brown's definition of 'loam' prevents the ranking of soil textures with regard to star shake with the same confidence as with ring shake. However, reference could be made to the contemporary US classes (USDA, 1938), which did include an individual category for loam. This corresponds mainly to the sandy silt loam category of the current Avery system, with more minor overlaps with the clay loam and sandy loam categories. Since the current Forestry Commission soils identification guidance (Kennedy, 2002) also defines 'loamy' soils as those within these same three categories and as Brown's data indicate a medium-to-high risk of star shake on any texture other than clay, it might therefore be concluded that only clay soils represent a low risk of star shake and that other influences will always be highly important on other site types.

The data support Brown's conclusion that shake may appear on almost any site, but also highlight the importance of distinguishing between the two types of shake both for research and for forest planning purposes.

Soil texture was also assessed by Henman (1986a) as part of a more limited review of (apparently very) shake-prone woodlands (Table 5). Although the study did not distinguish between the two types of shake, in all instances except for one these badly affected stands were planted on sandy or silty soils, with the majority on silt-based loams. Silt-based loams may be lightly or weakly structured when the clay fraction is low, making them prone to compaction on both the surface and in the upper horizons, in turn making them prone to run-off and impeded drainage (Environment Agency, 2007). Both factors are likely to affect the rooting environment and interfere with the uptake of moisture and nutrients. The absence of any predominantly clay-textured soils in this study should also be noted.

In a wider study (44 sites; not limited to shake-prone) Henman (1991) found that all soils with a clay content of >20% had a low incidence of shake. All crops with a high incidence occurred on sandy soils, but interestingly not all of the sandy sites were affected, indicating that other factors were modifying the potential of the sandy sites to produce shaken crops.

Both Brown and Henman's studies support the traditional broad associations of shake with sandy soils and absence with clay soils. Although the data must be considered with caution, Brown's work in particular highlights the importance of distinguishing between the two types of shake especially with regard to the high incidence of ring shake on sandy sites. Both studies imply that loamy soils, particularly those with a higher silt or sand content, may be more associated with star shakes. The significance of silt and silty loam soils as a shake risk does not appear to have been much considered and may indicate a useful subject for future research.

With regard to stone content, a study of harvesting sites in western Britain by Henman (1986a) quantified stone content according to percentage by volume. This enables a stoniness classification to be applied according to the current system for ecological site classification (ESC; Table 6). Although sample size was quite varied and not all soil factors were assessed, 'moderate', 'very' and 'extremely' stony sites were shown to be associated with high or very high incidences of shake (not quantified according to shake type). A further survey of blown trees in south and east England following the 1987 storm by Henman and Denne (1988) also found the highest incidence of shake to occur on 'stony soils derived from a variety of parent materials'. Later studies by Henman (1991) found that stone-free sites were nearly always shake free, that all oak woodlands on gravels had a high incidence of shake, and that a very high microsite stone content was often associated with shake in an individual tree (although no **direct** statistical association between stoniness and shake could be determined, indicating that other factors needed to be considered).

Table 5 Relationship of soil texture (Avery classes) to the incidence of shake within stands (nine different shake-prone sites; from Henman, 1986a).

Soil texture	Number of trees assessed	Incidence (% of trees affected)	Severity
Silt loam	52	44	Most moderate–severe
Silt loam	28	54	Even across classes
Sandy loam	53	62	Even across classes
Silty clay loam	49	63	Most slight–moderate
Silt loam	25	64	Even across classes
Silty clay loam	160	66	Even across classes
Sandy clay	32	75	Even across classes
Sandy loam	16	88	Most slight–moderate
Silt loam	15	100	Most moderate–severe

Henman (1991) proposed that soil richness is probably critical since sites on calcareous soils with a relatively high stone content were shown to be significantly less affected than those on less rich soil but with a similar stone content, as long as rooting depth was not otherwise restricted. Soils on richer sedimentary lithologies were also less shake-prone where a higher stone content was derived from the bedrock and was friable, which may indicate that a controlled and ongoing release of soil minerals may mitigate the other negative effects of stoniness.

The class descriptions and actual percentages used for Henman's 1991 study were not specified, although there are references to 'high' stone content in relation to poor rooting conditions and 'very stony' in association with free drainage. Since the study pre-dated the current ESC system (Table 6), and given that the contemporary literature used percentage classes for soil description that differ quite widely from ESC, it can probably be assumed that Henman's 'very' would now be classed as 'extremely'. However, the modern classes can certainly be used for evaluation in terms of higher or lower stone content and these can now be considered broadly, along with other factors, in order to assess the overall shake risk for a particular site.

Table 6 Index and class descriptions of stoniness (Pyatt, Ray and Fletcher, 2001).

Description	Percentage
Stone-free	0% of soil volume
Slightly stony	<5% of soil volume
Moderately stony	5–15% of soil volume
Very stony	16–30% of soil volume
Extremely stony	>30% of soil volume

Does the evidence enable recommendations for management?

Soil texture is likely to be a complex factor. Traditional assumptions that clay soils are better and sandy soils worse for shake are well supported by what empirical evidence is available, but this relationship appears to be strong only in the case of ring shake and there are indications that climatic factors in relation to windiness and constancy of water table are also important. Star shake is the most prevalent form of the defect and badly affected stands appear to occur on a far wider range of site types, with only clay soils (>35% clay content) at relatively low risk. Both studies indicate that silt loam soils may be of relatively high risk in terms of star shake. Note, however, that heavy clay soils (>55% content) may be prone to waterlogging, depending on climate and topography, and might therefore need to be considered as higher risk.

Although the data must be treated with caution, the quite extensive records compiled by Brown do enable a tentative ranking of soil textures with regard to the risk of star shake (only), and highlight an apparent (if perhaps unexpected) risk associated with loamy soils with a higher silt content. All soil textures other than clay soils in the range of 35–55% clay fraction appear to be prone to star shake.

It is proposed, therefore, that soil texture should certainly be considered as a key factor, but be thought of in terms of relative **overall** risk (Table 7) and always with regard to other associated shake hazards. Careful site selection and silviculture, with ongoing protection, are likely to be of paramount importance. Vulnerable individuals should be identified for thinning as early as possible on the basis of late flushing, damage, obvious defects, and lean and sinuous growth, particularly on higher risk sites.

Table 7 Indicated level of shake risk according to predominant soil texture (Avery classes). Note: Soil texture should not be regarded as the single determining factor – other triggers will always be important.

Ring shake – significance as a trigger	Soil texture (predominant type)
Very low	Clay (<55% clay content)
Low	Clay loam
	Silty clay loam
Medium (in no particular order of rank)	Clay (>55% clay content)
	Sandy clay
	Silt loam
High	Sandy loam
	Sand

Star shake – significance as a trigger	Soil texture (predominant type)
Low	Clay (<55% clay content)
Not yet determined on the basis of evidence, but likely to be medium to higher risk (in no particular order of rank) although highly influenced by other factors	Clay loam
	Silty clay loam
	Clay (>55% clay content)
	Silt loam
	Sandy loam
	Sandy clay
	Sand

There is quite strong evidence associating stoniness with shake. While the limits defining lower or higher risk have not been entirely defined by empirical data, the studies indicate that only stone-free or slightly stony sites (and microsites), that is those with <5% stone content by volume, should be considered as lower risk.

Detailed analysis of soil moisture status is unlikely to be practical in terms of a shake risk assessment. However, some impression of the vulnerability of a site and soil to repeated episodes of drought or waterlogging may be obtained by considering its overall character in terms of slope, substrate, soil texture and stone content (see sections on these other triggers).

Substrate and lithology

Historical and anecdotal evidence primarily refers to soil texture as the main influence on shake development: factors which are largely dependent upon the parent lithology.

Scientific evidence

Records of wartime fellings of oak (>100 years old) by the Forestry Commission were reviewed and tabulated by Brown (1945). Analysis focused largely on soil texture (see previous section) but usefully the report also includes full descriptions of contemporary lithology enabling the data to be re-presented here according to the more modern classifications (Tables 8 and 9).* It has also been possible to distinguish between the two types of shake.

Again, Brown's data must be treated with caution due to potential errors in identifying shake but since the lithology data are likely to have been derived from standard geological survey maps they may be more reliable than the soil texture data.

With regard to ring shake, the data indicate very low risks associated with chalk, clay (unless flints are present), carboniferous and mudstone substrates. Higher risks appear to be associated with sandstone substrates (except for Old Red).

Table 8 Relationship of substrate to ring shake (extracted from Brown, 1945) updated to the modern lithology classifications.

Lithology	*n* stands assessed	*n* trees assessed	% of trees with ring shake
Chalk	2	15	0
Carboniferous (Coal Measures)	2	16	0
Clay + sandstone	1	12	0
Mudstone + limestone	1	18	0
Sandstone + mudstone + limestone	1	20	0
Shale + clay + limestone	3	65	0
Shale + mudstone + sandstone	1	25	0
Mudstone	3	106	0
Clay	6	143	1
Sandstone (Old Red) (fine-to-medium)	4	61	3
Shale	2	83	4
Superficial deposits (glacial or alluvial)	17	504	4
Clay + flints	2	45	4
Clay + sandstone (Millstone Grit) (coarse)	2	37	5
Shale + limestone	1	50	6
Limestone	6	263	6
Clay + limestone	2	45	7
Sandstone (Sherwood) (fine-to-medium)	1	25	16
Sandstone (Bunter) (fine)	3	115	18
Sandstone (Millstone Grit) (coarse)	2	58	19
Sandstone (New Red) (fine-to-medium)	3	78	27

* Data entries that have been excluded from this summary are: i) entries for stands <100 years old (only partially done by Brown, who nevertheless recognised the significance of tree size in shake development), ii) entries with vague or qualitative data (e.g. 'generally sound', 'negligible', 'few'), and iii) entries (two only) with geological descriptions that are too broad to translate into the modern lithological classifications.

Table 9 Relationship of substrate to star shake (extracted from Brown, 1945) updated to the modern lithology classifications.

Lithology	*n* stands assessed	*n* trees assessed	% of trees with star shake
Chalk	2	15	0
Clay	6	143	0
Clay + sandstone	1	12	0
Sandstone + mudstone + limestone	1	20	0
Carboniferous (Coal Measures)	2	16	6
Mudstone	3	106	9
Sandstone (Old Red) (fine-to-medium)	4	61	10
Sandstone (Bunter) (fine)	3	115	10
Superficial deposits (glacial or alluvial)	17	504	12
Sandstone (New Red) (fine-to-medium)	3	78	13
Clay + flints	2	45	16
Shale	2	83	16
Shale + mudstone + sandstone	1	25	16
Clay + sandstone (Millstone Grit) (coarse)	2	37	16
Mudstone + limestone	1	18	17
Sandstone (Millstone Grit) (coarse)	2	58	22
Limestone	6	263	24
Shale + clay + limestone	3	65	25
Clay + limestone	2	45	27
Sandstone (Sherwood) (fine-to-medium)	1	25	28
Shale + limestone	1	50	60

Shale, Old Red sandstone, and limestone (except where interbedded in low proportions) indicate a low-to-medium risk, as do the presence of any superficial deposits. For star shake, as with soil texture there is a broader and generally higher risk associated with lithology, except for sites on chalk and clay (without flints), which are also very low. Limestone is indicated as a consistently high risk substrate. Otherwise carboniferous, mudstone, sandstone, superficial deposits and shale substrates (probably in that order) all indicate a middling risk. Clay sites with embedded flints suffered significant levels of shake, supporting the findings by Henman mentioned earlier concerning stoniness in the overlying soil.

The low incidence on chalk-derived soils is likely to be due to higher levels of free calcium and also to good moisture availability, since some chalk soils are believed to be quite drought resistant (even if shallow) due to the porous nature of the underlying substrate and the potential for upward moisture supply to deeper root systems, especially on more level sites (Wilson *et al*., 2008; Jason Hubert, personal communication). Conversely, the incidence of shake on limestone substrates was relatively high, so despite the likely ready availability of calcium there are probably other significant risk factors such as shallow and rocky soils with high potential for drought. However, limestone sites in North Wales and the northern Marches mostly had a high incidence of shake while those in eastern England were relatively low, so the presence of a more oceanic climate, wider fluctuations in rainfall and the higher mechanical stresses of wind and exposure could be important additional triggers.

Sites on mud rock substrates were generally affected, but only significantly so with regard to star shake for which shale appears to be a higher risk than mudstone. There is probably insufficient evidence to distinguish definitively between shale and mudstone sites in terms of vulnerability, although Henman (1991) proposed that more friable types may have an advantage in terms of sustained and long-term release of nutrients.

Sites with a sandstone substrate were quite widely affected, mostly with a medium–high incidence, and few sites were unaffected. It is important to distinguish between shake types with regard to sandstone lithologies, since there are indications of a very strong association with ring shake but less so for star shake. All of the study sites on New Red sandstones developed sandy or sandy loam soils and all were badly affected (>25%). On Old Red sandstone, however, only half of the sites suffered shake, again badly, but half were unaffected. Two of the three unaffected stands were on sites with clay loam soils indicating that, on Old Red sandstones at least, an assessment of soil texture may be particularly important in determining higher or lower shake risk. Henman (1991) noted that soils derived from Old Red sandstone were typically more fertile than those from other types. Brown's study included no data for sites on the more friable types of sandstone (i.e. green or yellow), although a number of sites on greensand were later assessed by Henman (1991; see below). Hypothesising that there may be associated influences related to drainage (e.g. percolation rates and soil texture) and also differences in available nutrients, the author of this report has attempted to add an assessment of grain size to the sandstone types. No conclusions could be drawn from the limited data available, although this aspect may be suitable for future study.

Brown's research presents strong evidence that sites on superficial deposits (i.e. glacial drift, alluvial deposits or any other unconsolidated material) are moderately shake-prone. The presence of this material (especially gravel beds) is likely to encourage very free drainage within the soil profile and increase susceptibility to drought and leaching of nutrients. Any deposits are also likely to have been mixed within the lower horizons through soil creep and may further inhibit root development and the uptake of nutrients. It is highly likely that the same principles will apply to disturbed ground and to engineered soils, for example reclaimed drift mine workings and landscaped spoil heaps.

The relationship between substrate and shake within stands was also noted in later studies by Henman (1986a, 1991). Although the surveys were limited to known shake-prone sites and do not differentiate between ring and star shake, the evidence (Table 10) also supports the association with sandier substrates and indicates a lower incidence on chalk or clay sites, with a variable but relatively high incidence on mudstone and shale. These studies, perhaps more so than Brown's, indicate that shake can appear on almost any substrate but, importantly, with regard to chalk sites Henman (1991) found that those with higher nutrient levels and higher clay content were the least affected. Also, a predominantly igneous (granite under clay) site was included in the earlier study and found to be quite badly affected, perhaps supporting the historical associations with shake in Devon and Cornwall (Henman, 1986a).

Does the evidence enable recommendations for management?

Although somewhat limited, the evidence demonstrates that shake can occur almost everywhere and on most substrates, albeit with a higher incidence on certain types. Sites with alluvial deposits or glacial drift material overlying the bedrock should always be considered risky (seemingly more so for star shake than ring shake), although a relatively constant water table and a milder climate may mitigate this. Chalk substrates appear to be of lowest risk but this may be dependent on the overall proportion of clay particles within the soil. Clay substrates also indicate lower risk unless interbedded with other lithologies (particularly limestone or flint material), as do mudstone and carboniferous lithologies. Sandstone is likely to indicate a higher risk unless of the Old Red type, which may benefit from a higher clay fraction than other types. Shale substrates also indicate a generally higher risk. Limestone always appears likely to be high risk. Note that star shake is the most prevalent form of the defect and appears to be represented across a wider range of substrates.

Otherwise geological factors may be too complex to enable any absolute associations to be made. It is therefore proposed that substrate should be considered as a key factor but be considered in terms of relative **overall** risk (Table 11) and always with regard to other associated factors.

Note: Despite the low shake risks associated with chalk, species such as ash, beech and sycamore are usually recommended for planting where top soils are calcareous. Pedunculate oak may be a suitable choice, however, on chalk soils where a suitable clay fraction has developed (see previous), where rooting depth (see next section), soil nutrition and water holding capacity are also adequate, and where pH does not exceed about 7.5.

The British Geological Survey (BGS) geological map sheets may be useful to help with identifying the substrates for a particular site, although the small scale of the paper editions (1:625 000) can make it difficult to pinpoint individual stands especially in areas of complex lithology. Alternatively, large-scale digital maps (1:50 000) are now available to view online and free of charge at the BGS OpenGeoscience website (open the *Geology of Britain* viewer) and can be used to identify the location of even relatively small woodlands. The viewer incorporates a query function which provides adequate detail regarding both the bedrock lithology and any superficial deposits (if present) to indicate whether a site may be shake-prone in respect of these key characteristics.

Available rooting depth

The depth of soil available for both rooting stability and the uptake of moisture and nutrients is likely to be a very significant factor influencing the overall risk of shake.

Scientific evidence

Henman (1991) found that on shake-prone sites affected trees were almost twice as common on areas of shallow soil (<50 cm) than on deeper soil. Data for various studies relating to root depth and spread were collated by Crow (2005), who was able to group soils according to their physical and hydrological properties and publish probable rooting-depth requirements for the normal development of various tree species. For pedunculate oak (only), these are indicated as follows:

- to 1.0 m depth in shallower soils over rock;
- to 1.5 m depth in soils with moisture-retaining upper horizons;
- to 1.5 m depth in soils with wet lower horizons;
- to 4.0 m depth in intermediate loamy soils.

No other studies relating to soil or rooting depth have been identified.

Table 10 Relationship of substrate to incidence and severity of shake, both within and between stands (limited to known shake-prone sites only; from Henman, 1986a, 1991).

Substrate	Number of trees assessed	Number of stands assessed	Incidence (% Affected by shake)	Severity	Study
Clay	52	n/a	44	Most moderate–severe	1986b
Shale + sandstone	28	n/a	54	Even across classes	1986b
Granite under clay	12	n/a	58	Even across classes	1986b
Clay	53	n/a	62	Even across classes	1986b
Mudstone + sandstone	49	n/a	63	Most slight–moderate	1986b
Shale	59	n/a	63	Most bad–severe	1986b
Shale	160	n/a	66	Even across classes	1986b
Sandstone	15	n/a	100	Most moderate–severe	1986b
Chalk	n/a	6	13	n/a	1991
Clay	n/a	9	38	n/a	1991
Sandstone (green)	n/a	6	52	n/a	1991
Sandstone (Old Red)	n/a	3	71	n/a	1991

Table 11 Indicated level of shake risk according to predominant substrate type. Note: Lithology should not be regarded as the single determining factor – other triggers will always be important.

Ring shake – significance as a trigger	Substrate (predominant type)
Lower	Chalk
	Carboniferous
	Clay (unless flints present)
	Mudstone
Lower to medium	Sandstone (Old Red)
	Shale
	Superficial deposits
	Limestone
Higher	Sandstone (all types other than Old Red)

Star shake – significance as a trigger	Substrate (predominant type)
Lower	Chalk
	Clay (unless flints present)
Lower to medium	Carboniferous
	Mudstone
	Sandstone (Old Red)
Medium to higher	Sandstone (New Red)
	Sandstone (Bunter)
	Superficial deposits
	Shale
Higher	Sandstone (Sherwood)
	Sandstone (Millstone Grit)
	Sandstone (green/friable)
	Limestone

Does the evidence enable recommendations for management?

Although soil depth has been relatively little studied, there are several other risk factors associated with shallowness such as stability and growth stress (see later section on page 20), to low soil moisture and perhaps also to high stone content (see earlier section on page 13), which is likely where soil cover is thin. On the basis of the available evidence and accounting for the other risk factors naturally associated with thinner soils, a higher risk of shake can be expected where available rooting depth is limited to <50 cm. However, there are further indications that a minimum available depth of at least 1.0 m would need to be available for development of a normal root system, and at least 1.5 m on soils more typically associated with the production of higher quality timber. The presence of compaction or any other impermeable layer in the soil profile will have a similar limiting effect unless otherwise ameliorated by cultivation.

Mechanical stresses (external forces)

The forces of wind, severe cold temperatures and the de-stabilising effects of slope are directly related to the altitude and topography of a site. Each is likely to be an important trigger of shake and is discussed separately below.

Wind

Features such as large earlywood vessels, healed stem wounds, or areas of decay or wetwood are structural defects and are considered to represent significant predispositions to shake. Stress caused by the forces of wind may concentrate at these locations and trigger shakes, either by shearing woody tissue in areas where cell adhesion has been weakened or by extending any existing separations within the wood structure.

Scientific evidence

Postal questionnaire data summarised by Henman (1991) demonstrated a fairly common belief that higher elevations and exposed aspects are associated with shake. However, empirical studies by Brown (1945) and by Henman (1991), which were primarily concerned with other physical site factors, did not find sufficient evidence to support associations with wind, elevation or aspect. Brown, while observing that the 'stormier areas of the west' were more likely to yield crops with shake, concluded that the worst affected crops were in fact no more exposed than any others, although the report contained only a limited discussion of method and the analysis appears to be more arithmetic than statistical.

The forces of even very strong winds are not believed to induce shakes in healthy wood (i.e. the internal stresses associated with bending and twisting are insufficient to shear normal cells within a growth ring), but exposure will naturally have an influence on the extent of mechanical and growth stresses experienced by a growing tree and the importance of wind as a trigger of existing predispositions to shake is believed to be high (Henman, 1991). No literature relating specifically to the study of wind effects was found, however, and the association remains unverified.

Wind is known to be a significant cause of stem wounding via abrasion or limb breakage, so may also be responsible for initiating predispositions in otherwise sound trees. Higher elevation sites will be subject to other trigger factors, since they typically have shallower and rockier soils and may be prone to drought or waterlogging, depending on slope form.

Does the evidence enable recommendations for management?

Available evidence is insufficient to enable quantifiable recommendations to be made in terms of exposure (i.e. a specific wind hazard class or DAMS score). Shake risk is likely, however, to increase with exposure and elevation, not least due to wounding from stem abrasion and breakage, especially where other site risk factors are present. Note that the Forestry Commission system of ecological site classification (ESC; Pyatt, Ray and Fletcher, 2001) specifies DAMS scores of up to 12 as very suitable for the establishment of both sessile and pedunculate (native) oak woodlands, with 12 to 18 suitable and above 18 unsuitable.

Severe cold temperature

The mechanisms whereby severe cold causes localised wounding (or wider structural damage to growth rings) and initiates a predisposition were discussed earlier. The effects of freezing temperatures as a trigger are likely to be of greater importance, however, and are relatively easily observed. Although there may be little appreciable or economic difference when the defects are visible in cut logs, frost crack and shake are normally described as separate phenomena (Savill, 1986; Savill and Kanowski, 1993). The two are closely associated, however, and, having the same effect on the timber, a frost crack has also been described as an 'exacerbated' form of shake or an 'associated phenomenon' (Henman, 1991). In any case frost cracks can be a very useful, but not entirely reliable, indicator of the presence of shake within a standing tree.

Scientific evidence

Severe cold weather can lead to the freezing and expansion of the fluid within bacterial wetwood (see earlier section on page 6) or existing shakes, forcing it outward and initiating a frost crack which may eventually penetrate the sapwood, cambium and bark. (The same process may also partially explain why new star shakes often appear to have initiated from an existing ring shake.)

Frost cracks may heal more or less effectively: a healing wound is still likely to be visible for some years as a seam (Figure 5), but may also be aggravated by continuous reopening in subsequent winters leading to the formation of a prominent rib (Figures 6 and 7) due to the repeated in-rolling and separation of successive layers of healing tissue (Rishbeth, 1982; Kubler, 1983). Note that rib-like features may also have their origin in other aspects of tree architecture and should not be taken as a reliable indicator of the presence of shake.

Figure 5 Seam indicating a partially healed frost crack. Note the corresponding split in the wood beneath it. In this instance the dark staining is not thought to be bacterial wetwood and may be associated with a *Phytophthora*.

Sandra Denman.

Figure 6 Prominent rib caused by the ongoing reopening and healing of a frost crack originating in bacterial wetwood (dark stained area).

Joseph O'Brien, USDA Forest Service; used according to US FS creative commons licence.

Figure 7 Severe and unhealed frost crack that may have originated in the extensive ring shake.

USDA Forest Service, Northeastern Area Archive; used according to US FS creative commons licence.

Henman (1991) found that frost cracks were always accompanied by shakes, although French studies of both pedunculate and sessile oak have also identified a significant correlation between the winter moisture content of healthy stem sapwood and frost crack formation in individual trees (Cinotti, 1989), so frost cracks may not always have their origin in shakes. Some other types of wound, once healed, may also give rise to similar looking features.

Does the evidence enable recommendations for management?

Frost hollows and areas of waterlogged ground should be avoided, as these are likely to increase susceptibility to frost cracking and the aggravation of any existing predispositions, especially where wetwood or a high sapwood moisture content exist. Trees with obvious stem fissures, seams or ribs should be identified and considered for removal during thinning, as it is highly likely that some gross structural defect will be present if not actual shake.

There may also be opportunities for future tree improvement programmes if suitable individuals with a lower sapwood moisture capacity can be identified (Henman, 1991), although this trait was not selected for in the current Future Trees Trust oak breeding programme mentioned earlier.

Steep slope

Although steeper ground has historically been associated with shake (Henman, 1991), the effects of slope have been very little studied and no direct association with shake has been proven. However, soils on steeper ground are typically thinner, rockier and freer-draining than their counterparts on more level areas, so growing trees are likely to be disadvantaged in terms of rooting conditions and water availability. Steep ground is also often associated with exposed locations where a higher incidence of lean (support stress), wind sway (mechanical stress) and wounding (from abrasion and limb breakage) will be encountered.

Scientific evidence

Henman (1991) classified 44 study sites according to four grades of classification (flat, gentle, medium and steep); 33 of the sites were on flat or gently sloping ground and 11 on steep ground (there were no study sites in the medium category). Incidence of shake was assessed in three classes: 0–30%, 31–50% and 51–100% affected. A large majority (73%) of the sites with a steep slope were found to be in the worst category of shake prevalence while flat or slightly sloping sites had quite an even spread of shake between the three classes. Microsite differences are also likely to be important: within one individual site the majority of trees on medium or steep ground were severely shaken whereas the majority on level ground were only slightly shaken.

The class limits were not quantified or referenced in Henman's study and the differences in terminology do not enable direct comparison with the Forestry Commission's published system of terrain classification (Table 12). It is therefore proposed to adopt the official classifications for the purposes of site vulnerability assessment with a direct interpretation of Henman's 'flat' as level, 'medium' as moderate, and 'steep' as including both the steep and very steep classes.

Table 12 Forestry Commission slope classification system (after Rowan, 1977; updated Forestry Commission, 1996).

Class	Description	Limits (slope percentage)	Limits (slope in degrees)
1	Level	0–9	0–5
2	Gentle	10–19	6–10
3	Moderate	20–32	11–17
4	Steep	33–49	18–26
5	Very steep	50+	27+

Trees grown on steep slopes are also known to have a high proportion of tension wood (Henman, 1991), which **may** also represent a predisposition to shake and is currently under investigation by Forest Research.

Does the evidence enable recommendations for management?

While a steep slope should perhaps not be considered as a singular trigger of shake it should nevertheless be regarded as a likely indicator of the presence of other adverse factors. Existing research suggests that, for the purposes of higher quality timber production at least, slopes of >32% should be avoided especially where other soil characteristics are likely to be limiting. On low-lying and more level ground, however, there may be frost hollows or areas prone to waterlogging, so a small degree of slope may in fact be desirable.

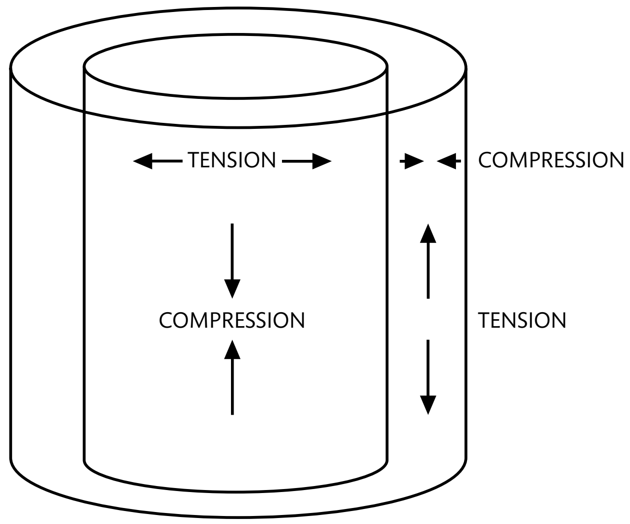
Growth/support stresses (internal forces)

Growth stress refers to the development and distribution of internal mechanical forces as a tree grows in diameter, height and overall mass. These exist both as support stresses, caused by the tree supporting its own weight (influenced by geometry and architecture) and by resisting the prevailing winds, and also as maturation stresses when growing cells modify their dimensions (Faust, Fuller and Rice, 1996; Fonti, Macchioni and Thibaut, 2002). Maturation stresses have not been studied in relation to shake but it seems likely (Henman, 1991) that support stresses are important triggers when acting on existing defects, especially in large or leaning trees and those with very unbalanced crowns.

Scientific evidence

In an upright stem, internal support stresses generally occur radially as tension and longitudinally as compression within the inner two-thirds of stem diameter (Figure 8). Radial tensions start at and are highest close to the pith, increasing according to the rate of accumulating tension but not reaching the outer sapwood (which is in compression). In the outer third of stem diameter stresses occur longitudinally as tension and radially as compression, which may constrain splitting and explain why star shakes rarely penetrate the outer third in the absence of subsequent frost cracking. Internal support stresses naturally increase with diameter and are therefore believed to be more important as shake triggers than are any external stresses. In older, larger trees the tension forces in the central part of the trunk may be very substantial and are probably a significant shake trigger (Henman, 1986b, 1991; Kubler, 1987; Henman and Denne, 1992).

Figure 8 Illustration of the distribution of tension and compression forces in a 'typical' upright tree stem.



Henman (1986b) proposed that since support stresses naturally increase with tree size they are likely to be an important shake trigger when acting on any weak or otherwise abnormal areas of wood; that is, the overall mass becomes critical once a certain diameter is reached. It has been stated, based on research, that shake rarely occurs in trees below 35–40 cm in diameter (Henman 1986b; Henman and Denne, 1992). There may be differences regarding shake type in this respect since there is anecdotal evidence, based on a postal survey, that ring shake is uncommon at less than 45 cm diameter and star shake is rarely found below 30 cm (Henman, 1991). The significance of tree mass may be supported by historical felling records (Brown, 1945), which showed that the vast majority of shake-prone oak stands were more than 100 years old, although the data may be too limited to draw any useful correlation with age.

Although not directly studied it has been hypothesised by Henman (1991) and supported by Fonti and Sell (2003; in relation to sweet chestnut) that a substantial increase in growth stress will be experienced when a tree is subject to a sudden release of growth (e.g. after heavy thinning or the removal of competing coppice), since crown and main stem responses will rarely be fully balanced or proportionate.

Leaning trees in plantation are relatively common, often due to natural responses to available light but also to early instability especially where establishment is rapid or rooting conditions unstable. Many oak trees that have not grown straight will also display bowing effects in the bole; these effects may be simple but are often three-dimensional as a tree will naturally attempt to counterbalance any lean. Bow in more than one direction is referred to as sinuous growth and the complex stresses that arise from this morphology may also be significant as a shake trigger. Although not previously studied, lean and sinuosity are likely to be significant influences on shake development and are subjects of a current Forest Research study.

Visible stem splits or (healed) seams in otherwise sound individuals are believed to be caused by severe cold (see above) and not by tension or compression forces, although once formed they may be further aggravated by their action (Kubler, 1983; Savill, 1986; Henman, 1991).

Does the evidence enable recommendations for management?

Sites with exposed aspects, higher altitudes or subject to more oceanic climate conditions are sometimes characterised by leaning stems and imbalanced crowns. Support stresses are likely to be greater and more irregularly distributed than in trees grown at more sheltered locations, so the former sites can reasonably be considered to have a higher overall risk of shake. However, trees with no outward indications in the main stem might not necessarily be free of imbalanced growth stresses, but simply more effective at overcoming them (e.g. trees of otherwise good form at exposed locations).

When identifying trees for selective thinning it is usually standard practice to include any sinuous or otherwise poorly formed stems, or trees with a substantial crown imbalance. It may also be worth considering the removal of any individuals with very pronounced root buttressing or apparent spiral grain (usually visible in the overlying bark), since these may be indicative of efforts made to overcome other unbalancing forces. Swept stems that might normally be retained as potential higher value curved beams (e.g. for 'cruck' type applications) may also be at an increased risk of shake on otherwise risky sites.

Summary of evidence

While shake has traditionally been associated with sandy, rocky and gravelly soil types, very little empirical research on the subject was carried out until the 1970s. There is now a reasonably strong base of evidence, however, that the following factors will predispose a tree to shake:

- Large earlywood vessel diameter. Greater pore space reduces overall strength and creates potential fracture points. Vessel diameter is known to be highly heritable and seed orchards for improved material have now been established to produce planting stock without large vessels. There is also strong evidence, however, that diameter may be increased by higher water availability during vessel formation, so site factors are also likely to be important.

- Wounding to the main stem. Damage never fully heals and the presence of barrier tissue underlying healthy tissue is a potential fracture point as is the presence of wetwood formation.

- Abrupt changes in ring width. Drought or defoliation constrains summer growth and reduces ring width, while a sudden release of growth (e.g. from heavy thinning) increases it. In each instance the changes in wood structure adjacent to areas of 'normal' growth create a structural imbalance that may initiate fractures. Maintaining constancy of growth rate is therefore important if shake is to be avoided.

There is also fairly strong evidence that none of these 'predispositions' will lead to shake without an additional aggravating factor or 'trigger'. Important triggers are likely to be:

- poor soil nutrition, preventing the rapid and effective healing of wounds;
- soil conditions that impede the development of a firm and healthy rooting system, inhibit nutrient uptake and, especially, prevent constancy of the water table;
- mechanical stresses, due to the actions of wind, severe cold and steep slopes;
- growth/support stresses, due to natural tree architecture, size/age and gravity.

A holistic approach to assessing shake risk should be taken, based on all of the factors likely to be present for a given site (or tree).

A more detailed summary of the known or suspected influences on shake development is presented in Table 13, including an evaluation of the likely impact of each risk factor, whether other influencing factors are important, and also whether the existing knowledge may enable recommendations for the planning and management of new or existing oak plantations.

* Impact ratings are as follows:

High: likely to have a significant impact on shake development, where an associated predisposition or trigger risk factor exists

Medium: possible that there will be a significant impact on shake development, where an associated predisposition or trigger risk factor exists

Low: unlikely to have a significant impact on shake development

** Evidence base ratings are as follows:

Good: sound evidence base that includes scientific studies

Moderate: reasonable evidence base but no direct studies (may be indirect or associated studies)

Poor: small amount of evidence, poor understanding of factors

Table 13 Summary of evidence relating to factors influencing the development of shake in oak.

Risk factor	Rating of potential impact*	Strength of evidence for judgement**	Inherited or acquired risk?	Are other associated factors important?	Does the evidence enable recommendations for management?	
					New planting	Existing crop
(a) Predispositions						
Large earlywood vessel diameter	High	Good – empirical	Inherited and/or acquired	Yes: Mechanical or growth stresses are required to trigger	Yes: Use improved planting stock when becomes available. Use tree shelters judiciously	Yes: Remove late flushing trees early in rotation, or those that drop their leaves early
Wounding and barrier zone formation	High	Good – empirical	Acquired (but inherited genetic qualities may also influence)	Yes: Initial cause of wounding required. If soil nutrient status is low then healing will be slower and less effective. Mechanical or growth stresses are required to trigger	Yes: Avoid exposed sites and those with low-calcium soils. Protect trees from damage	Yes: Protect trees from damage. Identify trees with obvious decay and remove when thinning
Wounding and bacterial wetwood formation	Medium–high	Good – empirical	Acquired (but inherited genetic qualities may also influence)	Yes: Initial cause of wounding required. Mechanical or growth stresses are required to trigger. (Note that roots are also vulnerable to damage from drought or waterlogging)	Yes: Protect trees from damage, especially during harvesting and extraction. Avoid frost hollows and waterlogged ground	Yes: Identify trees with frost cracks and obvious decay and remove when thinning
Abrupt changes in ring width	High	Good – empirical	Acquired	Yes: Drought, defoliation or close competition may reduce ring width; sudden and heavy thinning may increase ring width	Yes: Avoid drought-prone sites and frost hollows	Clean and weed in early years. Ensure that thinnings are carefully marked and are carried out in time to ensure regular, even growth
Tension wood and **possible** localised variation in wood density	Unknown – not previously studied	None currently – association is now being tested	Acquired	N/a	N/a	N/a
(b) Triggers						
Physiological stress – **soil nutrition**	High	Good – empirical	N/a	Yes: Existing predisposition required (any)	Yes: Low available calcium and/or high aluminium content indicate higher risk	No
Physiological stress – **soil type**	Low–medium	Poor–moderate (evidence is mainly **inferred** by reference to more empirical soil studies of texture, water and nutrients)	N/a	Yes: Existing predisposition required (any)	Yes: Although only brown earth sites would normally be considered for oak in plantation, acid brown earths (pH 4.5–6.5) and gravelly or sandy brown earths are likely to be at higher risk than are calcareous or forest brown earth types	Yes: On riskier soil types, individuals subject to other predisposing factors are at higher overall risk, so remove during thinning
Physiological stress – **soil pH**	Low–medium	Poor–moderate (most evidence is **inferred** from calcium studies)	N/a	Yes: Existing predisposition required (any)	Yes: Soil pH may give a broad indication of likely available calcium	No

Table 13 Summary of evidence relating to factors influencing the development of shake in oak. (continued)

Risk factor	Rating of potential impact*	Strength of evidence for judgement**	Inherited or acquired risk?	Are other associated factors important?	Does the evidence enable recommendations for management?	
					New planting	Existing crop
(b) Triggers						
Physiological stress – **soil texture**	Medium–high	Good (clay and sandy soils) – empirical and observational Moderate (other soil types) – empirical and observational Note that effects differ according to shake type	N/a	Yes: Existing predisposition required (any)	Yes: Although some shake can be expected on **any** substrate, clay soils (35–55% clay) are certainly lower risk. Sandy soil types are higher risk but this is only strongly indicated with ring shake. Do not assume that other soils are low risk, particularly loams with a higher silt fraction. Other aggravating factors will always be important	Yes: Individuals subject to other factors are at higher overall risk, so remove during thinning
Physiological stress – **soil stone content**	Medium–high	Good – empirical and observational	N/a	Yes: Existing predisposition required (any)	Yes: A higher risk of shake can be expected where soil stone content is 5% or greater by volume	Yes: Individuals subject to other factors are at higher overall risk, so remove during thinning. Microsite is similarly affected
Physiological stress – **soil moisture content**	High	Good – empirical	N/a	Yes: Existing predisposition required (any)	Yes: Sites prone to waterlogging, drought, or highly fluctuating water table are likely to be at a higher risk. **Note: Constancy** of water table is probably highly important	Yes: Microsite is similarly affected, which may enable identification of vulnerable individuals or patches of ground
Physiological stress – **substrate and lithology**	Medium–high	Good – empirical and observational Note that effects differ according to shake type	N/a	Yes: Existing predisposition required (any)	Yes: Expect some shake on **any** substrate, but lower risk is associated with chalk, clay, carboniferous and mudstone lithologies; higher risk with sandstones other than Old Red; intermediate risk with limestone, shale, superficial deposits and Old Red sandstone. Other aggravating factors will always be important	Yes: Individuals subject to other factors are at higher overall risk, so remove during thinning
Physiological stress – **available rooting depth**	Medium–high	Good – empirical (limited) and observational	N/a	Yes: Existing predisposition required (any)	Yes: shake risk is highly increased if rooting depth is <50 cm	Yes: Individuals subject to other factors are at higher overall risk, so remove during thinning

Table 13 Summary of evidence relating to factors influencing the development of shake in oak. (continued)

Risk factor	Rating of potential impact*	Strength of evidence for judgement**	Inherited or acquired risk?	Are other associated factors important?	Does the evidence enable recommendations for management?	
					New planting	Existing crop
(b) Triggers						
Mechanical stress – **wind**	Medium	Moderate – largely observational or deduced	N/a	Yes: Existing predisposition required (any)	Yes: Avoid very maritime climates and higher elevations or exposed sites	Yes: Identify wind-damaged trees and remove during thinning
Mechanical stress – **severe cold temperature**	Medium–high	Moderate – empirical and observational	N/a	Yes: Existing predisposition required (usually bacterial wetwood)	Yes: Avoid frost hollows (especially) and higher elevation or exposed sites	Yes: Identify frost-cracked trees and remove during thinning
Mechanical stress – **steep slope**	Medium–high	Good – empirical and observational	N/a	Yes: Existing predisposition required (any)	Yes: Avoid sites with slope >32%, especially where other soil properties may be limiting	No
Growth/ support stress – based on tree size, shape and stability	Medium	Moderate – empirical and observational	N/a	Yes: Existing predisposition required (any)	Yes: Avoid exposed, steep or rocky sites	Yes: Consider limiting rotations and aiming for target diameters to avoid over-maturity on sites where other risk factors are likely to be significant. Favour upright, straighter stems when thinning on all sites. Root buttresses and spiral grain may also indicate higher risk

Finally, this review has indicated the importance of distinguishing between the two shake types in order to better understand their causes. On the basis of the evidence reviewed there are strong indications that the three known shake predispositions have a greater significance for one type than the other, as do the presence of sandy soil types and parent material (Table 14).

Table 14 Risk factors and their likely most associated shake types, where indicated as more likely to be associated with one than the other.

Ring shake		Star shake	
Risk factor	Strength of association	Risk factor	Strength of association
Abrupt change in ring width	High	Large mean vessel diameter	Medium–high
Wounding to **trunk** with subsequent barrier zone formation	Medium	Wounding to **root-collar** or **roots** with subsequent barrier zone formation	Medium
Sandy soil	High	Low soil clay fraction (<20%)	Medium

References

AVERY, B.W. (1980). *Soil classification for England and Wales (Higher Categories)*. Rothamsted Experimental Station, Harpenden.

BROWN, J.M.B. (1945). *Silvicultural data from war fellings. Ring shake and star shake in oak crops*. Unpublished Forestry Commission internal report, December 1945.

CHANG, C.I.J. (1972). The cause of ring shake: a review of literature. *Quarterly Journal of Chinese Forestry* **6**, 69–77.

CINOTTI, B. (1987). *The influence of wood structure in oaks (*Quercus robur *L. and* Q. petraea *Liebl.) on their susceptibility to frost crack*. Thèse D.E.A. Sciences du Bois, Centre de Recherchés Forestièrès, Champenoux 54280 Seichamps

CINOTTI, B. (1989). Winter moisture content and frost-crack occurrence in oak trees (*Quercus petraea* Liebl. and *Q. robur* L.). *Annales des Sciences Forestièrès* **46**, 614–16.

CROW, P. (2005). *The influence of soils and species on tree root depth*. Information Note FCIN078. Forestry Commission, Edinburgh.

DEFRA (2013). *Government Forestry and Woodlands Policy Statement*. Defra Forestry Policy Team, London.

DENNE, M.P. and HENMAN, G.S. (1990). *Control of wood quality in British oaks*. HGTAC Technical Sub-committee Paper 776. School of Agricultural and Forest Sciences, University of Wales, Bangor.

ENVIRONMENT AGENCY (2007). *Think soils: identifying soil structural problems in the field*. [Internet] Environment Agency, Bristol.

EVANS, J. (1984). *Silviculture of broadleaved woodland*. Forestry Commission Bulletin 62. Forestry Commission, HMSO, London.

FAUST, T.D., FULLER, M. and RICE, J.T. (1996). Occurrence of compression wood in hurricane-stressed pine pole timber. In: H.L. Haymond, D.D. Hook and W.R. Harms (eds), *Hurricane Hugo: South Carolina forest land research and management related to the storm*. USDA Forest Service General Technical Report SRS-5, pp. 189–93. USDA Forest Service Southern Research Station, Asheville, North Carolina.

FONTI, P. and GARCÍA-GONZALES, I.G. (2008). Earlywood vessel size of oak as a potential proxy for spring precipitation in mesic sites. *Journal of Biogeography* **35**, 2249–57.

FONTI, P., MACCHIONI, N. and THIBAUT, B. (2002). Ring shake in chestnut (*Castanea sativa* Mill.): state of the art. *Annales des Sciences Forestièrès* **59**, 129–40.

FONTI, P. and SELL, J. (2003). Radial split resistance of chestnut earlywood and its relation to ring width. *Wood and Fiber Science* **35** (2), 201–208.

FOREST RESEARCH (2012). Oak defoliators: biotic factor that contributes to oak decline [Internet]. Forest Research, Edinburgh [www.forestry.gov.uk/fr/infd-7b3d8v]. Accessed April 2015.

FORESTRY COMMISSION (1996). *Terrain classification*. Technical Note 16/95. Forest Research, Technical Development Branch, Ae, Scotland.

GARCÍA-GONZALES, I.G. and ECKSTEIN, D. (2003). Climatic signal of earlywood vessels of oak on a maritime site. *Tree Physiology* **23**, 497–504.

HENMAN, G.S. (1986a). *Investigation of oak shake by UCNW – a review*. M102 Home Grown Timber Advisory Committee Paper No. 679 (unpublished). Forestry Commission, Edinburgh.

HENMAN, G.S. (1986b). Growing sound timber – shivers and shakes. In: G.C. Barnes (ed.) Occasional Paper 16: *Forestry Section Proceedings, Annual Meeting of the British Association for the Advancement of Science*, Bristol, 1–5 September 1986. Forestry Commission/HMSO, London.

HENMAN, G.S. (1991). *Shake defects in British oaks*. PhD Thesis, University College of North Wales, Bangor.

HENMAN, G.S. and DENNE, M.P. (1988). Control of shake in oak. In: *Forestry Commission Report on Forest Research* 1988, HMSO, London.

HENMAN, G.S. and DENNE, M.P. (1992). *Shake in oak*. Research Information Note No. 218. Forestry Commission, Wrecclesham.

KANOWSKI, P.J., MATHER, R.A. and SAVILL, P.S. (1991). Short note: genetic control of oak shake; some preliminary results. *Silvae Genetica* **40** (3/4), 166–8.

KENNEDY, F. (2002). *The identification of soils for forest management*. Forestry Commission Field Guide. Forestry Commission, Edinburgh.

KUBLER, H. (1983). Mechanism of frost crack formation in trees – a review and synthesis. *Forest Science* **29** (3), 559–68.

KUBLER, H. (1987). Growth stresses in trees and related wood properties. *Forest Products Abstracts* **10**, 61–119.

McGINNES, E.A., CHANG, C.I.-J. and WU, K.Y.-T. (1971). Ring shake in some hardwood species: the individual tree approach. *Journal of Polymer Science* **36** (1), 153–76.

McGINNES, E.A., PHELPS, J.E. and WARD, J.C. (1974). Ultrastructure observations of tangential shake formation in hardwoods. *Wood Science* **6**, 206–11.

McGINNES, E.A. and WU, K.Y.-T. (1973). Intra-incremental chemical studies of ring shake in scarlet oak. *Wood Science* **5**, 287–94.

MATHER, R.A., KANOWSKI, P.J. and SAVILL, P.S. (1992). Shake in oak. *Oxford Forestry Institute Occasional Papers* **41**, 46–9. University of Oxford, Oxford.

MATHER, R.A. and SAVILL, P.S. (1994). The commercial impact of oak shake in Great Britain. *Forestry* **67** (2), 119–31.

PRICE, A.J.E. and MUNRO, G. (2011). *Shake assessment and log valuation for a known shake-prone site*. Unpublished internal summary paper. Forest Research, Edinburgh.

PRICE, A.J.E. and SAVILL, P. (2013). Acoustic velocity measurements of oak – do these assist in detecting shaken stems? *Quarterly Journal of Forestry* **107** (3), 192–6.

PYATT, G., RAY, D. and FLETCHER, J. (2001). *An ecological site classification for forestry in Great Britain*. Forestry Commission Bulletin 124. Forestry Commission, Edinburgh.

RISHBETH, J. (1982). *Bacterial wetwood*. Arboriculture Research Note 20/80/PAT. Issued by the DOE Arboricultural Advisory and Information Service, Wrecclesham.

ROWAN, A.A. (1977). *Terrain classification*. Forestry Commission Forest Record 114. HMSO, Edinburgh.

SAVILL, P.S. (1986). Anatomical characters in the wood of oak *(Quercus robur* L. and *Quercus petraea* Liebl.) which predispose trees to shake. *Commonwealth Forestry Review* **65**, 109–16.

SAVILL, P.S. and KANOWSKI, P.J. (1993). Tree improvement programmes for European oaks: goals and strategies. *Annales des Sciences Forestièrès* **50** (1), 368–83.

SAVILL, P.S., KANOWSKI, P.J., GOURLAY, I.D. and JARVIS, A.R. (1993). Short note: genetic and intra-tree variation in the number of sapwood rings in *Quercus robur* and *Q. petraea*. *Silvae Genetica* **42** (6), 371–5.

SAVILL, P.S. and MATHER, R.A. (1990). A possible indicator of shake in oak: relationship between flushing dates and vessel sizes. *Forestry* **63** (4), 355–62.

SCOTTISH EXECUTIVE (2006). *The Scottish Forestry Strategy 2006*. Scottish Executive/Forestry Commission Scotland, Edinburgh.

SHIGO, A.L. (1972). Ring and ray shakes associated with wounds in trees. *International Journal of the Biology, Chemistry, Physics and Technology of Wood* **26** (2), 60–2.

SHIGO, A. and LARSON, E. van H. (1969). *A photo guide to the patterns of discolouration and decay in living hardwood trees*. United States Department of Agriculture, Forest Service Research Paper NE-127. United States Department of Agriculture, Forest Service, North-eastern Forest Experiment Station, Newtown Square, Pennsylvania.

SHIGO, A. and MARX, H.G. (1977). *Compartmentalisation of decay in trees*. USDA Agriculture Information Bulletin 405. United States Department of Agriculture, Forest Service, Washington D.C.

USDA (1938). *Soil textural triangle* [Internet]. United States Department of Agriculture, Natural Resources Conservation Service. [www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/edu/?cid=nrcs142p2_054311] Accessed April 2015.

WARD, J.C. and PONG, W.Y. (1980). *Wetwood in trees: a timber resource problem*. General Technical Report PNW-112. United States Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

WELSH ASSEMBLY GOVERNMENT (2009). *Woodlands for Wales. The Welsh Assembly Government's Strategy for Woodlands and Trees*. Welsh Assembly Government/Forestry Commission Wales, Cardiff.

WILSON, S.McG., BROADMEADOW, M., SANDERS, T.G. and PITMAN, R. (2008). Effect of summer drought on the increment of beech trees in southern England. *Quarterly Journal of Forestry* **102** (9), 111–120.

ZAHNER, R. (1969). Site quality and wood quality in upland hardwoods: theoretical considerations of wood density. In: C.T. Youngberg and C.B. Davey (eds) *Tree growth and forest soils*. Proceedings of the Third North American Forest Soils Conference, pp. 472–497, North Carolina State University, Raleigh, North Carolina.

ZIMMERMANN, M.H. (1983). *Xylem structure and the ascent of sap*. Springer-Verlag, New York.

Shake (internal splitting of the wood in a growing tree) is believed to affect and devalue around one-fifth of British oak crops. There is currently no fully reliable method to identify the defect in standing trees, or to predict vulnerable sites and stands without local knowledge and historical data. Shake may appear on any site, even those with the fewest natural hazards. The purpose of this review is to enable the riskiest sites to be identified and avoided for new planting and to help lower risk sites be managed in order to minimise their potential for shake. Evidence suggests that the following factors will predispose a tree to shake:

- Large earlywood vessel diameter. Greater pore space reduces overall strength and creates potential fracture points.
- Wounding to the main stem. Damage never fully heals and the presence of barrier tissue underlying healthy tissue is a potential fracture point as is the presence of wetwood formation.
- Abrupt changes in ring width. Changes in wood structure adjacent to areas of 'normal' growth create a structural imbalance that may initiate fractures.

There is also fairly strong evidence that none of these 'predispositions' will lead to shake without an additional aggravating factor or 'trigger'. Important triggers are likely to be:

- poor soil nutrition, preventing the rapid and effective healing of wounds;
- soil conditions that impede the development of a firm and healthy rooting system, inhibit nutrient uptake and, especially, prevent constancy of the water table;
- mechanical stresses, due to the actions of wind, severe cold and steep slope;
- growth/support stresses, due to natural tree architecture, size/age and gravity.

There is a need for a holistic approach to assessing shake risk, based on all of the factors likely to be present for a given site (or tree). A distinction must be made between ring shakes and star shakes, since the findings clearly indicate that each predisposition favours a particular type. The summary tables presented at the end of the report have the potential to form the basis of a 'shake risk assessment'.

Forestry Commission

Silvan House
231 Corstorphine Road
Edinburgh
EH12 7AT

www.forestry.gov.uk