New Forests (2020) 51:1–19
https://doi.org/10.1007/s11056-019-09717-w

REVIEW

A review of the suitability of eucalypts for short rotation forestry for energy in the UK

A. D. Leslie[1] · M. Mencuccini[2] · M. P. Perks[3] · E. R. Wilson[4]

Received: 29 May 2018 / Accepted: 26 March 2019 / Published online: 1 April 2019

Abstract

Eucalyptus has been identified as a genus with potential for short rotation forestry in the UK. This article assesses the suitability of *Eucalyptus* for biomass production. The first part of the article compares *Eucalyptus nitens* and *Eucalyptus gunnii* against short rotation forestry (SRF) species proposed by Hardcastle (A review of the impacts of short-rotation forestry, LTS International, Edinburgh, 2006), while the second part discusses limitations to the growing of eucalypts in the UK and how they may be overcome. Eucalypts compare favourably with other tree species in the UK in terms of rapid growth (up to 30 $m^3\ ha^{-1}\ y^{-1}$) over short rotations of 10–15 years. The only genus that is potentially as productive in the UK is *Nothofagus*. Furthermore, most species will readily coppice, enabling regeneration after damage and avoiding the costs of replanting. The wood characteristics compare positively with other SRF species, exhibiting a moderate wood density, but limitations are a relatively high moisture and chlorine content. Many of the SRF species listed in Hardcastle (2006) are now damaged or under threat from damage by exotic pests or diseases. Eucalypts are currently relatively free from such damage. It is cold temperatures that most limits the use of eucalypts in the UK. Eucalypts, particularly when young are vulnerable to damage from cold weather events, particularly when temperatures drop rapidly. However, the risk can be reduced by planting appropriate species and provenances, facilitating rapid growth as smaller trees are more vulnerable and by focusing on species that coppice following damage.

Keywords *Eucalyptus* · United Kingdom · Short rotation forestry · Biomass

✉ A. D. Leslie
Andrew.leslie@cumbria.ac.uk

[1] National School of Forestry, University of Cumbria, Ambleside Campus, Rydal Road, Ambleside LA22 9BB, UK

[2] CREAF, University Autonomous Barcelona, Campus de Bellaterra, Edifici C, 08193 Cerdanyola Del Vallès, Barcelona, Spain

[3] Centre for Forestry and Climate Change, Forest Research, Northern Research Station, Roslin, Midlothian EH25 9SY, UK

[4] Walsh Fellow in Silviculture, University College Dublin Forestry, Belfield, Dublin 4, Ireland

Introduction

In the United Kingdom (UK) there are two main aims of the Government's Renewable Energy Strategy (DECC 2012); to reduce emissions of carbon dioxide and to improve energy security. This is to be achieved through producing 15% of the energy in the UK through renewable means by 2020, which represents an increase of seven times the 2009 contribution within a decade (DECC 2012). The lead scenario generated within the Strategy suggests that 30% of electricity and 12% of heat could be provided through use of renewable sources of energy (DECC 2012). By 2014, 7% of energy was derived from renewable sources, of which 72% was obtained from bioenergy (DECC 2015). Of this approximately 40% was from wood or other plant biomass (DECC 2015). The transition from fossil fuels to renewable sources of energy has been supported by the Renewable Heat Incentive (RHI) and the Feed-In Tariff (FIT). The RHI is focussed on providing payments to encourage the production of heat from renewable energy sources (OFGEM 2019a), while the FIT is aimed at increasing renewable electricity generation (OFGEM 2019b). The FIT scheme is closing to most applications in April 2019 but the RHI continues.

As a source of renewable energy, biomass has certain attractions; it can produce energy at times of peak demand, it involves low fossil fuel inputs for production and tried and tested technology is available for its efficient conversion. The UK Bioenergy Strategy (DECC 2012) predicted that while biomass imports will form the bulk of supply, domestic production can provide an important, stable and reliable resource. If demand for biomass were to be met domestically, the area under energy crops would need to increase dramatically. The UK Biomass Strategy (DEFRA 2007) anticipated that 350,000 ha of perennial energy crops would be required by 2020, which contrasts with the 2009 area of 15,500 ha of Short Rotation Coppice (SRC) and *Miscanthus* (SAC 2009). Woody biomass is an attractive option compared with agricultural biomass crops as it requires the input of relatively low levels of fertiliser, pesticides and herbicides and can also be established on marginal land, thereby not competing with food production (Hastings et al. 2014).

Two approaches to bio-energy production using tree species have been adopted: short rotation coppice (SRC) and short rotation forestry (SRF) (Read et al. 2009). These two approaches are compared in Table 1. Since the 1990s the development of dedicated woody energy crops in the UK has focused on using SRC of clones of willow (*Salix* spp.) or poplar (*Populus* spp.). However, a comparative analysis of both systems identified SRF using fast growing tree species as being the most cost-effective and time-efficient approach to reducing greenhouse gases (Matthews and Broadmeadow 2009). However, there are very few examples of SRF in the UK, with the largest plantation an area of 24.2 ha of eucalypts established at Daneshill in Nottinghamshire, eastern England as an energy forest (Wooddisse[1] pers comm). SRF contrasts with conventional production forestry in several ways. Conventional production forestry uses conifers, which are more productive than broadleaves in the UK over traditional rotations of 40–70 years. Normally SRF does not include thinning during the rotation, whereas after canopy closure production forestry stands are thinned on a cycle of 5–10 years. Due to the short rotation, measures are taken to accelerate establishment and maximise growth such as highly intensive weed control and fertiliser application (Purse and Leslie 2016b).

[1] Land Management Officer, Nottinghamshire City Council.

Table 1 Characteristics of SRC and SRF (modified from SAC 2009)

	SRC	SRF
Production practices	Established at high planting densities using willow cuttings which are harvested every 2–4 years	Established from transplants at lower planting densities and harvested every 8–12 years
Inputs	Pre-planting herbicide. N application in year 2 after cutting. Few additional inputs	Pre-planting herbicide. N application to reflect crop uptake and maintain crop vigour. Few additional inputs
Yields	7–12 Mg (oven dried) ha^{-1} y^{-1}	5–15 Mg (oven dried) ha^{-1} y^{-1} estimated–depending on species

Table 2 Attributes of the ideal SRF tree crop

Silvicultural/agronomic attributes	Wood property characteristics	Environmental characteristics
Fast growth and high biomass yield (Guidi et al. 2013), with mean annual increment (MAI) peaking early	Higher density wood in SRF species resulting in higher energy outputs per unit volume (Ramsay 2004)	Low negative impacts on the environment, such as soil nutrients and moisture (Ranney and Mann 1994).
Resistant to pests and diseases and extremes in climate, such as cold and drought	Wood with a low moisture content and other characteristics that reduce the drying requirement (Senelwa and Sims 1999)	Reproductive or other characteristics that limit the likelihood of invasiveness (Gordon et al. 2011) or hybridisation with native populations of trees (Felton et al. 2013)
The ability to coppice (Dickmann 2006, Hinchee et al. 2009, Guidi et al. 2013), or to sucker which avoids the costs of replanting and also enhances growth rates in the second and subsequent rotations (Dickmann 2006, Hinchee et al. 2009, Guidi et al. 2013)	Wood with suitable chemical characteristics for combustion (Senelwa and Sims 1999)	
Produces straight stems; lowering harvesting, handling and transportation costs (Walker et al. 2013)	Wood attractive to markets other than biomass, reducing market risk	

The silvicultural attributes of an ideal SRF tree crop are described in Table 2. Ideally it should grow rapidly, with mean annual increment peaking early, have a low environmental impact and the wood should have ideal properties of a fuel, such as low moisture content and appropriate chemical composition. A review by Hardcastle (2006) identified species and genera with potential for SRF in the UK, these being ash (*Fraxinus excelsior*), alder (*Alnus glutinosa*), birch (*Betula pendula*), *Eucalyptus gunnii*, *Eucalyptus nitens*, *Nothofagus* spp, poplar (*Populus* spp.) and sycamore (*Acer pseudoplatanus*). Of these ash, alder, birch and some poplars are tree species native to the UK. Since the publication of Hardcastle's (2006) report, the introduction of exotic pathogens has reduced the viability of some species, e.g., ash dieback (*Hymenoscyphus fraxineus*) on ash (Thomas 2016).

In the UK there has been research to identify site suitability criteria for eucalypts through an understanding of the limitations to survival and growth (e.g., Evans 1980, 1986; Purse and Richardson 2001; Leslie et al. 2011, 2012). However, the scale of planting of eucalypts in the UK has been modest; in the 5 years between 2011 and 2016 nurseries in the UK have sold about 220,000 seedlings (Purse and Leslie 2016b), which represents less than 100 ha of establishment. As such, there remains uncertainty about the risks of large-scale planting of *Eucalyptus* SRF in the UK.

In this review paper, we compare eucalypts with other appropriate species or genera as a source of biomass for energy production then identify the limitations of eucalypts in the UK and potential ways in which they may be overcome. There was found to be limited literature on short rotation forestry in general in the UK. The review has therefore relied on compiling information from two sources. The first is literature on cold-tolerant eucalypts that has been collected by the authors over a period of 15 years and includes material no longer on-line. The information on other species, has relied on extracting relevant material from publications covering more general aspects of the silviculture, growth and wood properties of the tree species. A constraint to comparing growth of SRF species is that there were few data for trees grown under intensive short rotation management in the UK. Whilst yield models have been developed for commercial stands under longer rotations these only provide estimates of stand growth after canopy closure (from 10 to 25 years of age) depending on the maximum mean annual increment (Edwards and Christie 1981).

This review is timely as recent research studies (e.g., Harrison 2011; Leslie et al. 2014b; McEvoy 2016; Leslie et al. 2018) and reviews (e.g.. McKay 2011; Leslie et al. 2012; Purse and Leslie 2016a, b) have led to a better understanding of the potential of eucalypts but also their limitations. The findings are focused on the UK, but are relevant to other areas with cool oceanic temperate climates in western Europe.

Yield of eucalypts and other SRF species

The main attraction of eucalypts is their high productivity, being among the most productive trees in the UK. Volume growth rates have been estimated from small plot trials, to be as high as 30 m^3 ha^{-1} y^{-1} for *E. nitens* (Purse and Richardson 2001). In Ireland a plantation of *E. nitens* felled at 16 years of age, with 740 stems ha^{-1}, yielded a mean annual increment (MAI) of 26.1 m^3 ha^{-1} y^{-1} (Hutchinson et al. 2011). Historic Forestry Commission data provides evidence of MAIs of 16 m^3 ha^{-1} y^{-1} for *E. gunnii* over a 20 year rotation (Leslie et al. 2018). Purse and Richardson (2001) conclude that higher yields of 10–15 oven dry Mg ha^{-1} y^{-1} (approximately 20–30 m^3 ha^{-1} y^{-1}) over 8–10 year rotations are possible from plantations of *E. gunnii*. In Redmarley, Gloucestershire in the south of England

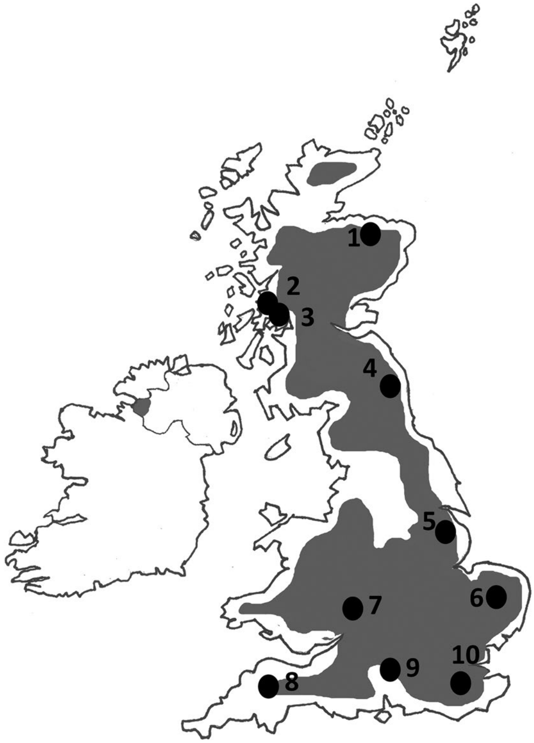

Fig. 1 Locations of sites with shaded area representing the − 14 °C minimum temperature monthly lowest (January) isotherm for (1961-90) (Met Office no date). The locations are as follows: (1) Moray, (2) Kilmichael, (3) Glenbranter, (4) Wark, (5) Daneshill, (6) Thetford, (7) Redmarley, (8) Exeter, (9) New Forest, (10) Chiddingfold

(Fig. 1), *E. gunnii* was estimated to have grown at a MAI of 25 m^3 ha^{-1} y^{-1} over a 11 or 12 year rotation (Purse and Richardson 2001). The coppice from this stand was assessed at 10 years of age and the standing volume of mainly *E. gunnii* with some *E. dalrympleana* combined was 317 m^3 ha^{-1} or 31.7 m^3 ha^{-1} y^{-1} with 4746 stems ha^{-1} (McKay 2010). Furthermore, when *E. gunnii* and *E. nitens* that had been damaged or killed by extreme cold in the winter of 2010–2011 was harvested at Daneshill in Nottinghamshire in the north of England (Fig. 1) at 5 years old an average of 85 Mg were extracted per hectare giving a green weight production of 17 Mg ha^{-1} y^{-1} (Wooddisse pers comm).

While eucalypts can be highly productive in the UK yields vary considerably across sites due to edaphic and climatic conditions, the quality of silvicultural practices and the genotype of the planting stock (Kerr and Evans 2011). This was highlighted by a study of four trials from the 1980s that demonstrated the difficulties in consistently achieving high levels of productivity (Kerr and Evans 2011). It was only at one trial at the New Forest (Fig. 1), in southern England where the potential of fast growth of eucalypts was realised; biomass at 7 years of age of *E. gunnii* and *E. glaucescens* was at least three times that of the other species planted, which were *Alnus cordata*, *Nothofagus obliqua*, *Populus balsamifera* and *Pteryocarya* x *rehderiana*. This trial was planted at two spacings and the results showed that increasing stocking significantly increased yield over a 7 year rotation. For *E. gunnii* a MAI of 2.7 m^3 ha^{-1} y^{-1} was achieved at 2.8 m spacing and of 13.9 m^3 ha^{-1} y^{-1} at 1.4 m spacing. For *E. glaucescens* the respective MAI was 8.1 m^3 ha^{-1} y^{-1} and 17.4 m^3 ha^{-1} y^{-1}.

SRF species should exhibit a peak in mean annual increment (MAI) at a relatively young age. The potentially most productive genus other than *Eucalyptus* is *Nothofagus*

Table 3 Estimates of mean annual increment and biomass yield for potential SRF species (cf. Hardcastle 2006)

Species	Mean MMAI ($m^3\ ha^{-1}\ y^{-1}$) and range	Biomass yield Mg $ha^{-1}\ y^{-1}$ (oven dried)	Specific gravity	Green moisture content
Eucalyptus nitens	26–30[7]	N/A	0.45[9], 0.435–0.446[21]	56.2–59.3%[21]
Eucalypts gunnii	16[6]	1.5–8.2[5]	0.50[11]	–
Nothofagus	14 (10–18)[3]	3.0–10.5[5]	0.6[12], 0.45–0.53[13]	–
Poplar	9 (4–14)[1]	4.2[5]	0.36[5] 0.335[14] (aspen 0.48[15])	64%[16], 49–56%[19]
Sycamore	8 (4 to12)[1]	0.6–5.7[5]	0.63[8] (MC 12–17%)	41%[16], 48%[22]
Alder	4.5–14.6[2]	0.9–4.8 (red alder)[5]	0.54[10] (MC 12%), 0.43–0.49[18]	53%[22]
Birch	4–10[4]	0.5–5.7[5]	0.662[17], 0.53[20]	43%[16]
Ash	6 (2–10)[1]	0.5–4.7[5]	0.674[11]	32%[17], 40%[23]

[1]Edwards and Christie (1981), [2]Claessens et al. (2010), [3]Tuley (1980), [4]Hynenen et al. (2009), [5]Kerr (2011) Table 16, [6]Leslie et al. 2018, [7]O'Reilly et al. (2014), [8]Hein et al. (2009), [9]Kibblethwaite et al. (2001), [10]Claessens et al. (2010), [11]AFOCEL(2004), [12] Tuley (1980), [13]USDA (no date), [14]Christersson (2010), [15]Harrison (2009), [16]Forestry Commission (2011), [17]Solid Fuel Association no date, [18]Milch et al. (2015), [19]Tharakan et al. (2003), [20]Cameron (1996), [21] Teagasc (2015), [22]Kent et al. (2009)

and UK yield models predict maximum mean annual increments (MMAI) of 10 to 18 $m^3\ ha^{-1}\ y^{-1}$ (Tuley 1980). The mid MMAI of this range for *Nothofagus* shows MAI peaking at 14.0 $m^3\ ha^{-1}\ y^{-1}$ at 29 years of age (Tuley 1980). Poplars have been used in short rotation coppice due to their rapid early growth (Mitchell et al. 1993) and have been predicted to produce yields of 30.5 $m^3\ ha^{-1}\ y^{-1}$ or 22 Mg $ha^{-1}\ y^{-1}$ (at 35% moisture content) at age 15 years (Forest Research 1997). Stokes et al. (2017) has demonstrated the fast growth of hybrid aspen (*Populus x wettsteinii*) and commercial hybrid poplar clones in two Scottish trials at Moray and Kilmichael (Fig. 1). An assessment was made after 22 growing seasons at Moray and 21 growing seasons at Kilmichael. Clones of commercial poplar hybrids attained an average height of 19.98 m and 14.15 m respectively and a diameter at breast height (dbh) of 39.98 cm and 24.29 cm. Hybrid aspen exhibited more rapid growth with a height of 17.38 m and dbh of 30.99 cm at Kilmichael. Native aspen (*Populus tremula*) grew more slowly, achieving a height of 10.75 m and dbh of 14.97 cm at Moray and a height of 6.54 m and dbh of 8.86 cm at Kilmichael.

A review of the silviculture of alder across Europe showed that current annual increment (CAI) peaks at 20 years and MAI at between 30 and 50 years (Claessens et al. 2010). In Europe sycamore also exhibits an early peak in CAI and MAI and it is described as growing more rapidly than beech (*Fagus sylvatica*) up to an age of around 40 years and as being more productive than ash, on both poor and fertile sites (Hein et al. 2009). In most European countries birch is slower growing than sycamore or ash (Hynynen et al. 2009). The mean and range of MMAI and biomass productivity for these SRF species are presented in Table 3, while biomass productivity is based on SRF rotations, the MAI of species other than the eucalypts is based on conventional silviculture and rotations.

Wood properties and important physiological and morphological characteristics

There are physiological, morphological and wood characteristics that are attractive in a SRF species. The first is the ability to coppice (Dickmann 2006; Hinchee et al. 2009; Guidi et al. 2013), as it avoids the costs of replanting and results in enhanced growth rates in the second and subsequent rotations (Pukkala and Pohjonen 1990). All tree species described in Hardcastle (2006) will coppice or sucker, except for *E. nitens* which has a very limited ability to coppice (Neilan and Thompson 2008). While birch coppices after cutting it only does so weakly and so this not a recommended means of regenerating stands (Cameron 1996). For eucalypts the ability to coppice also confers a degree of resilience to damage. During the winter of 2010–2011 stems and foliage of *E. gunnii* were killed at a planting at Daneshill, Nottinghamshire in the north of England, however many of the trees later produced coppice shoots and remain healthy to this date, whereas trees of *E. nitens* were killed. This supports the recommendation that in the UK, only species that coppice, such as *E. glaucescens*, *E. gunnii* and *E. rodwayi* (Sims et al. 1999) should be planted, rather than the few species like *E. nitens* that do not have this capability (Neilan and Thompson 2008).

For wood used for solid fuel, rather than conversion into liquid fuels, the main factors determining its suitability are moisture content, heating value, proportion of fixed carbon and volatiles, the ash content and the alkali metal content (McKendry 2002). Moisture content strongly affects the net heating value of wood when it is burned (Huhtinen 2006). There is considerable variation in moisture content between the tree species selected by Hardcastle (2006) (Table 3). Eucalypts have relatively high wood moisture content and experience in Ireland has shown that drying *E. gunnii* can be problematic. The wood only dried rapidly when the bark was removed and this itself was difficult using machinery because of its fibrous nature (Leslie 2013). The heating value of dry wood of different tree species varies relatively little with conifers having a higher value per unit of dry wood than broadleaves, due to higher lignin content and the presence of resins (McKendry 2002). However, wood density varies considerably between the tree species. Dense wood is an attractive trait for fuelwood (Senelwa and Sims 1999), as higher densities represent a higher mass of material and therefore energy per unit volume and allows a higher mass of wood to be transported per unit volume. Alder and poplar exhibit a low wood density, the eucalypts and *Nothofagus* moderate density and sycamore, ash and birch exhibit higher density wood (Table 3).

Many of the species have not been burned for energy on an industrial scale in contrast to short rotation coppice. Ash, is known to produce good domestic fuel wood (Savill 2013) while in Sweden, birch is widely used as a source of domestic heat (Hedberg et al. 2002). A study of the effects of torrefaction, a heating process that improved the quality of wood fuel in terms of combustion and gasification on wood from trees including birch, aspen and eucalypts showed that the two eucalypt species tested contained chlorine concentrations eight times that of aspen and six times that of birch (Keipi et al. 2014). Chlorine can be corrosive to boilers and pipework in power plants. High levels of chlorine have also been reported from eucalypts grown in Ireland (Teagasc 2015).

A regular, straight stem enables more efficient handling, storage and processing (Walker et al. 2013), although if the material is to be chipped on site when harvested this is less important. Potential SRF species known to exhibit good stem form include *E. nitens* (Neilan and Thompson 2008), *Populus* (Savill 2013) and silver birch (Hynynen et al. 2009), while the stem form of *Nothofagus alpina* is as good as poplar (Tuley 1980). The other

SRF species show a wide variation in stem form between individuals. Ash is sensitive to frost damage and this can result in poor stem form through death of the leader and so frost prone sites should be avoided (Dobrowolska et al. 2011). Sycamore shows considerable variation in stem form (Hein et al. 2009). Young alder often exhibits a straight stem with a compact pyramidal crown, but stem form becomes more variable as the trees age (Savill 2013). Stem form of *E. gunnii* is variable and often poor (Purse 2010; Marriage 1977), but improved material used in France exhibits good stem form (AFOCEL 2007).

Abiotic and biotic limitations

To be a productive tree for biomass, it must be well adapted to the abiotic and biotic environment. The following sections examine the limitations imposed on eucalypts and the other tree species identified by Hardcastle (2006).

Abiotic limitations

Most of the tree species in Hardcastle's (2006) list of potential SRF species are well adapted to climate of the UK and will grow well on a range of soil types. However, periods of low temperatures can be damaging to *Eucalyptus* spp. and *Nothofagus* spp. (Deans et al. 1992). Eucalypts are at the margins of their climatic limits in most of the UK: over the last decade there have been two winters (2009–2010 and 2010–2011), with extended periods of < -10 °C overnight temperatures, causing widespread mortality to *E. gunnii* and *E. nitens* across a range of experimental sites planted in England (Harrison 2011) and in Scotland (McEvoy 2016). However, 2009–2010 was the coldest winter in 30 years and in some parts of England in 100 years (Prior and Kendon 2011) and 2010–2011 was only a little less severe (Met Office 2011). Furthermore, in a review of the impact of climate change on eucalypt plantations in general, Booth (2013) assessed their vulnerability as being moderate. He also noted that the short rotations often associated with eucalypts, compared with conventional forest rotations offered greater opportunities to change genotypes and silvicultural practices. Murray et al. (1986) noted the high risk of *Nothofagus* being damaged: however, if southern provenances are used and the hardiest individuals are selected, they are suitable for planting in most lowland parts of the UK.

Biotic limitations

The risk of damage to trees from biotic agents is predicted to increase (Logan et al. 2003, Sturrock et al. 2011) and is already having major impacts on forestry in the UK. European larch (*Larix decidua*) is no longer planted due to the impact of *Phytophthora ramorum* (Forestry Commission 2014), while planting of Corsican pine (*Pinus nigra* ssp. *laricio*) has ceased because of damage from *Dothistroma septosporum* (Brown and Webber 2008). Wainhouse et al. (2016) provide useful predictions of those pests and pathogens likely to be particularly damaging to trees in the UK in the future while another resource for appraising the risk from insect pests and pathogens is the online UK Plant Health Risk Register (UK Plant Health Risk Register no date). This does not provide a combined overall risk rating for a tree species. However, the risk from pests and pathogens to Hardcastle's (2006) potential SRF tree species can be broadly described as follows.

There are tree species currently at high risk from damage, such as ash which is no longer being planted due to the predicted damage from ash dieback (Woodward and Boa 2013). Furthermore, an additional risk is that from Emerald ash borer (*Agrilus planipennis*), which is now present in Russia (Straw et al. 2013), with the combined impacts likely to be severe (Thomas 2016). Sycamore can suffer extreme damage by grey squirrels (*Sciurus carolinensis*) and planting this species for timber is uneconomic in areas where high squirrel populations are present (Savill 2013). For pathogens of sycamore, Webber et al. (2011) note that *Phythophthora* spp and *Verticilium* wilt can be damaging in nurseries or newly planted stock. *Cryptostroma corticale* also affects sycamore and remains dormant in the tree until it becomes stressed by prolonged dry conditions and the pathogen then causes an ailment known as sooty bark disease, which results in crown dieback and can cause death of the tree (Savill 2013).

Of the tree species there are those where potentially serious pests or pathogens are already established in Britain. This group includes alder and *Nothofagus* which are at threat of damage from *Phytophthora alni* (Gibbs et al. 1999) and *Phytophthora pseudosyringae* (Scanu et al. 2012) respectively. This group also includes poplars, plantations of which have been severely damaged by rusts (*Melampsora* spp) in the UK (Forestry Commission 2005). Damage by *P. alni* was first noted in Britain 1993 primarily infecting and killing the native alder, but also grey alder (*A. incana*) and Italian alder (*Alnus cordata*) (Gibbs, et al. 1999). Other recent work (Černý et al. 2012) demonstrates that cold temperatures will kill the pathogen and suggests that with predicted increases in winter temperatures due to climate change, persistence of this pathogen may increase damage.

Infection by *P. pseudosyringae* of *Nothofagus* was first noted in 2009 in a stand of *N. obliqua* in Cornwall in the south of England, where in four plots between 50 and 72% of trees had become infected. The susceptibility of *Nothofagus* to this disease prompted Scanu et al. (2012, p. 27) to comment '*A consequence of this damaging new disease is that future use of N. obliqua* and *N. alpina* in *UK forestry as suitable species for climate change adaptation strategies could be limited*'. This view is supported by a recent review of *Nothofagus* in Britain (Mason et al. 2018) which identified *N. obliqua* and *N. alpina* as having potential, provided *P. pseudosyringae* does not prove to be highly damaging. Poplars are susceptible to attack by rusts (*Melampsora* spp). Rusts cause premature leaf fall and can also disrupt hardening in some hosts and other damage can include a reduction in growth, shoot die back and when severe, tree death. Developing varieties of poplar resistant to rusts and to the highly damaging *Xanthomonas populi* that causes stem cankers is the main strategy to produce disease free stands. In the past, the Forestry Commission published a list of resistant varieties (Forestry Commission 2005) and a mix of resistant clones was planted to reduce risk further, however at present there are no fully rust resistant varieties available (Tabbush and Lonsdale 1999).

Birch is currently relatively free of major damaging biotic agents, although it is susceptible to attack by *Armillaria* (Webber et al. 2011). Furthermore, there have been problems of crown dieback reported in recent plantings of birch, in Scotland, due to three pathogens; *Anisogramma virgultorum*, *Marssonina betulae* and *Discula betulina* (Green 2005). However, it is the threat from a pest, currently absent from the UK, that gives greatest cause for concern. The bronze birch borer (*Agrilus anxius*), if introduced would have a devastating impact (Nielsen et al. 2011) as silver birch and downy birch (*Betula pubescens*) are highly susceptible. Within 8 years of planting in a trial in the USA, all individuals of these birch species had been killed by the borer (Nielsen et al. 2011). The probability of detection of bronze birch borer in wood chips was extremely low using the current protocols in Europe (Okland et al. 2012), although the European and Mediterranean Plant Protection

Organisations (2011) risk assessment suggested current measures meant the likelihood of bronze birch borer arriving in Britain is relatively low.

Finally there are the eucalypts which currently are probably at the lowest risk of damage from pests and diseases in the UK as few native pests of eucalypts have been introduced to plantations outside Australia (Fanning and Barrs 2013). The eucalypts identified as being suited to SRF in Britain are not those most susceptible to *Phytophthora* spp or to foliar pathogens (Webber et al. 2011). There are no records of major pest outbreaks in the UK, however there have been outbreaks of pests in Ireland. In the late 1990s a psyllid, *Ctenarytaina eucalypti* was introduced to Ireland (Chauzat et al. 2002). Chemical control was not particularly effective and so a parasitic wasp, *Psyllaephagus pilosus* was introduced and this effectively controlled the psyllid (Chauzat et al. 2002). In 2007 a leaf beetle, *Paropsisterna selmani* caused severe defoliation in multi species plantings of eucalypts (Fanning and Barrs 2013, Horgan 2012). Fanning and Barrs (2013) describe the beetle as being a serious threat to eucalypts in Ireland, the UK and more widely in Europe as the adults are strong fliers, capable of surviving long periods without food and can tenaciously cling to various forestry residues.

Discussion

Eucalypts possess many of the silvicultural attributes that are attractive for SRF for biomass, namely rapid early growth, good stem form and methods for propagation and establishment that are well understood. This review of evidence supports the proposition that eucalypts could provide a productive source of biomass in the UK and in other countries with oceanic climates in Europe. In Ireland, well-adapted species of eucalypts have been identified (Neilan and Thompson 2008) and spacing and other trials are underway (Tobin et al. 2016). In France there has been a programme establishing pulp plantations of cold-tolerant eucalypts that has been established for 35 years in the mid-Pyrennes. About 2000 ha have been planted of *E. gunnii* and *Eucalypts x gundal*, its hybrid with *Eucalyptus dalrympleana* (FCBA 2018).

The climate of the UK however is generally colder than Australia and the parts of France where cold-tolerant eucalypts are planted. Over most of the UK absolute minimum temperatures dip to below − 14 °C over a 30 year period (Fig. 1), a temperature that will damage or kill most eucalypts, particularly young trees or when temperatures have dropped rapidly. It is mainly coastal or southern areas where absolute minimum temperatures remain higher (Met Office no date). Eucalypts are particularly vulnerable to cold damage because, unlike most temperate broadleaves they do not have a defined dormant period. Growth of the naked buds begins above a certain minimum temperature threshold, which contributes to their high productivity (Beadle et al. 1995). A study of *E. nitens* in Tasmania showed maximum winter growth rates were only marginally less than those in summer (Davidson et al. 1995). Hardening in cold-tolerant eucalypts usually commences below a temperature of between 2 °C (Paton 1983) and 4 °C (Davidson and Reid 1987) and there are differences between species in the rapidity of hardening and in the minimum temperature they will tolerate before damage. Work by Black (no date) in Ireland developed an index of hardiness for eucalypt species in Ireland based on lethal minimum temperature and rate of hardening and the index ranked species tested in the following order, from most hardy to least hardy; *Eucalyptus rodwayi*, *E. glaucescens, Eucalyptus subcrenulata, Eucalyptus delegatensis, E. gunnii, E. coccifera* and *E. nitens*. This is a useful approach, although it raises questions as to why *E. gunnii*, a highly cold-tolerant species ranked so low. Details of the provenance used was not provided and it may be that a less cold-hardy one was used.

The limited area of both *Eucalyptus* (Purse and Leslie 2016b) and *Nothofagus* (Mason et al. 2018) makes matching species to site imprecise but colder and more exposed sites must be avoided. To identify climatically suitable sites for planting *Nothofagus* and *Eucalyptus*, Ray and Sing (2006) created a map of England, Scotland and Wales that showed areas where minimum temperatures of −14 °C or below occur more than once every 50 years (Fig. 1) as a very broad indication of sites that had a low risk of cold damage (cf. Murray et al. 1986). An indication of relative cold of a site is currently not incorporated into Forest Research's Ecological Site Classification (ESC) (Pyatt et al. 2001) decision support system, a web-based programme for matching species to site.

An important means of reducing risk is ensuring suitable species and provenances of *Eucalyptus* are planted. Results from trials established in the 1980s (Evans 1986) or informal planting (Purse and Leslie 2016a) have yielded useful information on species and provenances that are well-adapted to parts of the UK. It is clear a wider range of eucalypts could be planted (Purse and Leslie 2016a) than *E. gunnii* and *E. nitens* as proposed in Hardcastle (2006) and incorporated into ESC. This has been recognised and the species most planted in the UK between 2011 and 2015 was *Eucalyptus glaucescens* (Purse and Leslie 2016b). Table 4 describes recommended provenances for five promising eucalypts and the areas of the UK where they are best suited. However, obtaining seed of superior provenances has proven difficult and it is likely that sub-optimal origins have been planted in recent decades in the UK.

The risk of damage by cold can be reduced further by focusing on species that readily coppice as they are likely to recover from the main stem being killed by cold and thus replanting costs can be avoided. Furthermore, coppice rotations are more productive than first-rotations (Pukkala and Pohjonen 1990). A further approach to reduce damage is the use of intensive silviculture to accelerate establishment and growth as larger trees are more resistant to cold than smaller ones (Leslie et al. 2014a). Finally, to reduce the risk of complete failure, plantations should comprise stands reflecting the full range of ages, from those recently established to those of rotation age, as younger stands are more susceptible to damage from cold.

A further positive influence on the suitability of eucalypts to the climate in the UK and other temperate maritime environments is the likely effect of climate change on the frequency and duration of extreme cold events. Climate models predict a reduction in the frequency of cold events during winters in Western Europe, and in general a reduced severity (Peings et al. 2013). Gloning et al. (2013) predict warmer winter temperatures and no increase in the frequency of extreme winter temperature events for the UK. However, warmer springs may lead to greater frost damage; a study by Augspurger (2013) at a woodland in Illinois, USA described increased risks of frost damage to woody species over the last 100 or more years associated with an increased frequency of periods of warming in March followed by frosts in April. The species other than eucalypts listed by Hardcastle (2006) are pioneer species and so their phenology is influenced more by photoperiod and less by temperature (Basler and Körner 2012). It is likely that climate change will extend their growing season, but this will also increase the risk of frost damage (Basler and Körner 2012). A potential negative factor for eucalypts are increased levels of carbon dioxide. Heightened levels (twice ambient concentrations) of atmospheric carbon dioxide have been shown to increase susceptibility to frost damage through an increased ice nucleation temperature in cold-tolerant eucalypts, probably caused by bacteria on the leaves (Lutze et al. 1998).

Table 4 Recommended origins for selected eucalypts

Species	Recommended origin	Source	Notes
E. delegatensis	Var *tasmaniensis* from Ben Lomond, Tasmania	One of the more cold hardy origins in Evans (1986) and confirmed in Leslie et al. (2014b)	Some mainland Australian origins are also hardy (Evans 1986). Recommended for warm areas of south west Britain with fast growth and good survival at a trial at Haldon Forest near Exeter. A valuable timber tree (FAO 1981)
E. glaucescens	Guthega, New South Wales	The most cold hardy of six origins in Evans (1986)	Adaptable to a range of sites and is unpalatable. One of the hardiest of eucalypts (Purse and Leslie (2016a)
E. gunnii	Lake MacKenzie, Tasmania	One of the most cold hardy origins in Evans (1986) and confirmed Cope et al. (2008)	Performs well over a range of locations but variable growth; at 3 years of age trees at Exeter were twice the height of those at Chiddingfold, Thetford, Glenbranter or Wark. (Leslie et al. 2018)
E. nitens	Higher altitude provenances from Victoria	Evans (1986)	Rapid growth but only to be planted in the least cold and least exposed sites.
E. subcrenulata	Mount Cattley, Tasmania	Evans (1986) recommended central or southern Tasmanian origins. Mount Cattley origin recommended in Leslie et al. (2014b)	To be planted in warm areas of south west Britain. Excellent survival and growth at a trial at Haldon Forest near Exeter (Leslie et al. 2014b)

Refer to Fig. 1 for locations of sites

The main constraints for using the wood from eucalypts as a source of biomass is the high moisture content and chemical composition of the wood. The high moisture content and requirement for some species for debarking for effective drying require additional inputs to produce a quality wood fuel. However, most of the plantations of woody energy crops in the UK have been SRC and wood from this source has as high a moisture content as eucalypt SRF. The high chlorine content of eucalypt wood creates acid gases and corrosion of boilers, however the concentration of chlorine can be considerably reduced (as much as 90%) by pre-heating the wood before burning through torrefaction (Kiepi et al. 2014).

If eucalypts were to be planted on a large scale in the UK, the environmental impacts would need to be quantified. The risk of invasiveness of *E. gunnii* and *E. nitens* is low. For both species, seed germination can be poor and the seedlings are susceptible to frost damage and, for *E. gunnii*, it is also palatable to deer. Furthermore, for both species the small seed size means that seedlings have few reserves and are vulnerable to competition from other plants; there are few UK sites where natural regeneration of *E. gunnii* has been observed and none where *E. nitens* has been recorded (Dickinson 2011a, b). In general, Booth (2013) highlights the low risk of invasiveness of eucalypts in frost prone areas of the world. *Nothofagus* is also not considered to be a threat and is included in the exotic tree species where planting is not regulated under the Wildlife and Natural Environment Act of 2011 (Forestry Commission Scotland 2015).

There are limited studies on the effects of eucalypts on flora and fauna in the UK. Surveys of fungi showed that most of the mycorrhizal fungi associated with eucalyptus had originated from Australia, with a limited number of native British species (Pennington et al. 2011), although another survey identified rare fungal species, including three species representing three new genera to the UK (Hobart 2012). A study of earthworms under SRF and in comparison with pasture (Rajapaksha et al. 2013) suggested SRF should focus on native species but also *Eucalyptus* spp, which also supported dense populations of earthworms. Under the Great Britain Non-native Species Risk assessments (Dickinson 2011a, b), reviews were conducted of the environmental risk associated with *E. gunnii* and *E. nitens*. The conclusion of the analysis for both species was that they were both in the upper level of the 'low' risk category for environmental impact.

In a review of predicted impacts of SRF on water quality and supply no problems were associated specifically with eucalypts, rather with intensively grown plantations (Nisbet et al. 2011). Furthermore, evidence shows that eucalypts are very efficient at using water to produce biomass (Dvorak 2012).

Conclusion

Eucalypts have many properties that make them attractive as a source of woody biomass in the UK. Where eucalypts have the greatest advantages is their potential growth rates that exceed those of the other species and are achieved over short rotations, although in practice high yields are often not achieved due to poor survival due to low temperatures. The risk of poor survival can however be mitigated by adopting four management approaches. The first is to focus on planting eucalypts that readily coppice as they are likely to recover from the main stem being killed by cold and thus replanting costs can be avoided. Furthermore, coppice rotations are more productive than first-rotations (Pukkala and Pohjonen 1990). A second means of reducing risk is the use of origins that have been proven to be best adapted to

UK conditions. There is a growing body of information on the most suitable provenances for a limited range of eucalypts (Table 4). A third approach to reduce damage is the use of intensive silviculture to accelerate establishment and growth as larger trees are less damaged by cold than smaller ones (Leslie et al. 2014a). Finally, plantations should comprise stands reflecting the full range of ages, from those recently established to those of rotation age, as younger stands are more susceptible to damage from cold.

The high moisture content of green wood and the high chlorine content released during their combustion (Keipi et al. 2014) are constraints to the use of eucalypt wood as a fuel. However, the moisture content is not higher than some other species, such as poplars (Table 3) and for SRC willow and methods have been devised for drying this material (Whittaker et al. 2018). The problem of chlorine release on combustion can also be addressed through pretreatment by torrefaction (Keipi et al. 2014).

Acknowledgements The authors would like to thank Professor Julian Evans and Dr Bill Mason for encouraging the writing of this review, originally as part of a PhD thesis. They would also like to acknowledge the assistance of Dr James Morison of Forest Research, the two anonymous referees and the editor for providing constructive comments on the draft manuscript.

References

AFOCEL (2004). Information *Eucalyptus, Eucalyptus* et environnement. Lettre d'information semestrielle eucalyptus. Numero 3, Vol. 2 Juillet 2004, AFOCEL, France

AFOCEL (2007) *Eucalyptus*: 35 ans d'experimentation dans le sud de la France. Informations Foret, No 2-2007, Fiche No 747. AFOCEL, France

Augspurger CK (2013) Reconstructing patterns of temperature, phenology, and frost damage over 124 years: spring damage risk is increasing. Ecol 94:41–50

Basler D, Körner C (2012) Photoperiod sensitivity of bud burst in 14 temperate forest tree species. Agric For Meteorolog 16:73–81

Beadle CL, Honeysett JL, Turnbull CRA, White DA (1995) Site limits to achieving genetic potential. In: Eucalypt plantations: improving fibre yield and quality. Proceedings CRC Temperate Hardwood Forestry-IUFRO Conference, pp 19–24

Black K (no date) Freeze tolerance of Eucalypt seedlings: a tool for assessing frost hardiness. Draft report, University College Dublin, Ireland

Booth TH (2013) Eucalypts and Their potential for invasiveness particularly in frost-prone regions. Int J For Res 1–7. http://www.hindawi.com/journals/ijfr/2012/837165/citations/. Accessed on 18 June 2015

Brown A, Webber J (2008) Red band needle blight of conifers in Britain. Forestry Commission Research Note 2. http://www.forestry.gov.uk/pdf/FCRN002.pdf/$FILE/FCRN002.pdf. Accessed 20 July 2017

Cameron AD (1996) Managing birch woodlands for the production of quality timber. Forestry 69:357–371

Černý K, Filipová N, Strnadová V (2012) Influence of low temperature and frost duration on *Phytophthora alni* subsp. *alni* viability. For Syst 21:337–342

Chauzat M-P, Purves G, Dunn R (2002) Release and establishment of a biological control agent, *Psyllaephagus pilosus* for eucalyptus psyllid (*Ctenarytaina eucalypti*) in Ireland. Ann Appl Biol 141:293–304

Christersson L (2010) Wood production potential in poplar plantations in Sweden. Biomass Bioenerg 34(9):1289–1299

Claessens H, Oosterbaan A, Savill P, Rondeux J (2010) A review of the characteristics of black alder (*Alnus glutinosa* (L.) Gaertn.) and their implications for silvicultural practices. Forestry 83:163–175

Cope MH, Leslie A, Weatherall A (2008) The potential suitability of provenances of *Eucalyptus gunnii* for short rotation forestry in the UK. Q J For 102:185–194

Davidson NJ, Reid JB (1987) The influence of hardening and waterlogging on the frost resistance of subalpine eucalypts. Aust J Bot 35:91–101

Davidson NJ, Battaglia M, Beadle CL (1995) Photosynthesis of *Eucalyptus nitens* is reduced by mild frosts. In: Eucalypt plantations: improving fibre yield and quality, pp 339–343

Deans JD, Billington HL, Harvey FL (1992) Winter frost hardiness of two Chilean Provenances of *Nothofagus procera* in Scotland. Forestry 62:205–212

DECC (2012) UK bioenergy strategy. Department for Transport, DECC, DEFRA. https://www.gov.uk/government/publications/uk-bioenergy-strategy. Accessed 23 April 2016
DECC (2015) Digest of United Kingdom energy statistics, DECC https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/450302/DUKES_2015.pdf. Accessed 23 April 2016
DEFRA (2007) UK biomass strategy, DEFRA. http://www.globalbioenergy.org/uploads/media/0705_Defra_-_UK_Biomass_Strategy_01.pdf. Accessed on 22 September 2017
Dickinson B (2011a) GB Non-native Organism Risk Assessment for *Eucalyptus gunnii*. GB Non Native Species Secretariat. http://www.nonnativespecies.org/downloadDocument.cfm?id=756. Accessed 6 Aug 2015
Dickinson B (2011b) GB Non-native Organism Risk Assessment for *Eucalyptus nitens*. GB Non Native Species Secretariat. http://www.nonnativespecies.org/downloadDocument.cfm?id=756A. Accessed 6 Aug 2015
Dickmann DI (2006) Silviculture and biology of short-rotation woody crops in temperate regions: then and now. Biomass Bioenerg 30:696–705
Dobrowolska D, Hein S, Oosterbaan A, Wagner S, Clark J, Skovsgaard JP (2011) A review of European ash (*Fraxinus excelsior* L.): implications for silviculture. Forestry 84:133–148
Dvorak WS (2012) Water use in plantations of eucalypts and pines: a discussion paper from a tree breeding perspective. Int For Rev 14:110–119
Edwards PN, Christie JM (1981) Yield models for forest management. Forestry Commission Bulletin 48. HMSO, London
European and Mediterranean Plant Protection Organisation (2011) Pest risk analysis for *Agrilus anxius*. https://secure.fera.defra.gov.uk/phiw/riskRegister/plant-health/documents/agrilusAnxius.pdf. Accessed 7 August 2015
Evans J (1980) Prospects for eucalypts as forest trees in Great Britain. Forestry 53:129–143
Evans J (1986) A Re-assessment of cold-hardy eucalypts in Great Britain. Forestry 59:223–242
Fanning PD, Barrs J-R (2013) Biology of the *Eucalyptus* leaf beetle *Paropsisterna selmani* (Chrysomelidae: Paropsini): a new pest of *Eucalyptus* species (Myrtaceae) in Ireland. Agric For Entomol 16:45–53
FAO (1981) Eucalypts for planting. FAO forestry series 11. FAO, Rome
FCBA (2018) L'eucalptus en France, production des plantations sur 3 rotations. https://www.fcba.fr/sites/default/files/fcbainfo-2018-10-eucalyptus-france-production-plantation-rotation-melun.pdf. Accessed 10 January 2019
Felton A, Boberg J, Bjorkman C and Widenfalk O (2013) Identifying and managing the ecological risk of using introduced tree species in Sweden's production forestry. Forest Ecol Manag 307:165–177
Forest Research (1997) Establishment and maintenance of a woodfuel resource. Bulletin 17/96. http://www.biomassenergycentre.org.uk/pls/portal/docs/PAGE/RESOURCES/REF_LIB_RES/PUBLICATIONS/GUIDANCE/ESTABLISHMENT%20AND%20MAINTENANCE%20OF%20A%20WOODFUEL%20RESOURCE%20TDB_TN1796.PDF. Accessed 7 June 2016
Forestry Commission (2005) Tree death in poplar plantations, summer 2005. www.forestry.gov.uk/pdf/fcwn11-05.pdf/$FILE/fcwn11-05.pdf. Accessed 9 August 2015
Forestry Commission (2011) Wood as fuel technical supplement. The Biomass Energy Centre
Forestry Commission (2014) *Phytophthora ramorum* - frequently asked questions. http://www.forestry.gov.uk/forestry/infd-5ubesn. Accessed 20 July 2017
Forestry Commission Scotland (2015) Managing invasive and non-native forestry species. Guidance for forest managers and owners. http://scotland.forestry.gov.uk/images/corporate/pdf/managing-invasive-and-non-native-forestry-species.pdf. Accessed 2 November 2017
Gibbs JN, Lipscombe MA, Peace AJ (1999) The impact of *Phytophthora* disease on riparian populations of common alder (*Alnus glutinosa*) in southern Britain. Eur J For Pathol 29:39–50
Gloning P, Estrella N, Menzel A (2013) The impacts of climate change on the winter hardiness zones of woody plants in Europe. Theor Appl Climatol 113:683–695
Gordon DR, Tancig KJ, Onderdonk DA, Gantz CA (2011) Assessing the invasive potential of biofuel species proposed for Florida and the United States using the Australian Weed Risk Assessment. Biomass Bioenerg 35:74–79
Green S (2005) Birch dieback in Scotland. Forestry Commission Information Note 72. http://www.forestry.gov.uk/PDF/fcin072.pdf/$FILE/fcin072.pdf. Accessed 22 August 2015
Guidi W, Pitre FE, Labrecque M (2013). Short-rotation coppice of willows for the production of biomass in Eastern Canada. In: Matovic MD (ed.) Biomas—now—sustainable growth and use. InTech, pp 421–448. http//intechopen.com/books/biomass-now-sustainable-growth-and-use. Accessed 18 June 2016
Hardcastle PD (2006). A review of the impacts of short-rotation forestry. LTS International, Edinburgh. http://www.forestry.gov.uk/pdf/SRFFinalreport27Feb.pdf/$FILE/SRFFinalreport27Feb.pdf. Accessed 27 June 2007

Harrison A (2011) Growing Energy Forestry: trials update, Research update presentation, 17 March 2009. https://www.forestry.gov.uk/pdf/Energy_Forestry_020611_Harrison_A.pdf/$FILE/Energy_Forestry_020611_Harrison_A.pdf. Accessed 9 August 2016
Hastings A, Tallis MJ, Casella E, Matthews RW, Henshall PA, Milner S, Smith P, Taylor G (2014) The technical potential of Great Britain to produce ligno-cellulosic biomass for bioenergy in current and future climates. Glob Change Biol Bioenerg 6:108–122
Hedberg E, Kristensson A, Ohlsson M, Johansson C, Johansson P, Swietlicki E, Veselya V, Wideqvista U, Westerholme R (2002) Chemical and physical characterization of emissions from birch wood combustion in a wood stove. Atmos Environ 36:4823–4837
Hein S, Collet C, Ammer C, Le Goff N, Skovsgaard JP, Savill P (2009) A review of growth and stand dynamics of *Acer pseudoplatanus* L. in Europe: implications for silviculture. Forestry 82:361–385
Hinchee M, Rottmann W, Mullinax L, Zhang C, Chang S, Cunningham M, Pearson L, Nehra N (2009) Short-rotation woody crops for bioenergy and biofuels applications. Vitro Cell Dev Biol Plant 45:619–629
Hobart C (2012) *Eucalyptus* a host for fungal aliens new to the UK. Field Mycol 13:51–56
Horgan FG (2012) Effects of leaf damage on oviposition choice in an invasive paropsine beetle. J Appl Entomolog 136:271–281
Huhtinen M (2006) Wood biomass as a fuel. https://www.hnee.de/_obj/CD8F42A0-B396-40E7…/5Eures_WoodPropertiesPDF.pdf. Accessed 3 January 2019
Hutchinson K, Thompson D, Berkery B (2011) The potential of *Eucalyptus* species as a source of biomass/Fibre in Ireland. Coillte. https://slideplayer.com/slide/5071591/. Accessed 28 Mar 2019
Hynynen J, Niemisto P, Vihera-Aarnio A, Brunner A, Hein S, Velling P (2009) Silviculture of birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.) in northern Europe. Forestry 83:103–119
Keipi T, Tolvanen H, Kokko L, Raiko R (2014) The effect of torrefaction on the chlorine content and heating value of eight woody biomass samples. Biomass Bioenerg 66:232–239
Kent T, Kofman P, Owens E, Coates E, Cooley S (2009) FORESTENERGY, Harvesting and processing forest biomass for energy production in Ireland. Coford, Dublin
Kerr G (2011) A Review of the growth, yield and biomass distribution of species planted in the English network trials of Short Rotation Forestry. In: McKay H (ed) Short rotation forestry: review of growth and environmental impacts. Forest Research Monograph, vol 2. Forest Research, Surrey, pp 135–164
Kerr G, Evans J (2011) Eucalypts for short rotation forestry: a case study from the 1980s. Q J Forest 105:109–117
Kibblethwaite RP, Johnson BI, Shelbourne JA (2001) Kraft pulp qualities of *Eucalyptus nitens*, *E. globulus* and *E. maidenii* at ages 8 and 11 years. N Zeal J For Sci 30:447–457
Leslie AD (2013) Eucalypts in the Republic of Ireland. Q J Forest 107:62–64
Leslie AD, Mencuccini M, Perks MP (2011) Eucalyptus in the British Isles. Q J Forest 205:43–53
Leslie AD, Mencuccini M, Perks MP (2012) The potential for *Eucalyptus* as a wood fuel in the UK. Appl Energ 89:176–182
Leslie AD, Mencuccini M, Perks MP (2014a) Frost damage to eucalypts in a short-rotation forestry trial in Cumbria (England). iForest 7:156–161
Leslie A, Mencuccini M, Purse JG, Perks MP (2014b) Results of a species trial of cold tolerant eucalypts in south west England. Q J Forest 108:18–27
Leslie AD, Mencuccini M, Perks MP (2018) Preliminary growth functions for *Eucalyptus gunnii* in the UK. Biomass Bioenerg 108:464–469
Logan JA, Régnière J, Powell JA (2003) Assessing the impacts of global warming on forest pest dynamics. For Ecol Environ 1:130–137
Lutze JL, Roden JS, Holly CJ, Wolfe J, Egerton JJG, Ball MC (1998) Elevated atmospheric [CO_2] promotes frost damage in evergreen seedlings. Plant Cell Environ 21:631–635
Marriage A (1977) Fast-growing firewood. Q J For 71:199–203
Mason B, Jinks R, Savill P, Wilson SM (2018) Southern beeches (*Nothofagus* species). Q J For 112:30–43
Matthews RW, Broadmeadow MSJ (2009) The potential of UK forestry to contribute to Government's emissions reduction commitments. In: Read DJ, Freer-Smith PH, Morison JIL, Hanley N, West CC, Snowdon P (eds) Combating climate change—a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change. The Stationery Office, Edinburgh, pp 139–162
McEvoy C (2016) Short rotation forestry trials in Scotland. Progress report 2015. http://scotland.forestry.gov.uk/images/corporate/pdf/energy-forestry-trials-progress-report-2016.pdf. Accessed 13 June 2017
McKay H (2010) Is planting Eucalypts a good idea? Powerpoint presentation at the National School of Forestry, Newton Rigg, 21 January 2010

McKay H (ed) (2011) Short rotation forestry: review of growth and environmental impacts. Forest research monograph 2. Forest Research, Surrey
McKendry P (2002) Energy production from biomass (part 1): overview of biomass. Bioresour Technol 83:37–46
Met Office (2011) Winter 2010/2011. http://www.metoffice.gov.uk/climate/uk/2011/winter.html. Accessed 3 Sept 2012
Met Office (no date) Minimum temperature monthly lowest (deg C) January 1961–90. Met Office. http://www.metoffice.gov.uk/climate/uk/averages/19611990/exn/1.gif. Accessed 12 June 2009
Milch J, Vavrcik H, Tippner J, Brabec M (2015) The effect of growth conditions in specific areas of Croatia and the Czech Republic on the physical and mechanical properties of black alder wood (*Alnus glutinosa* Gaertn.). Turk J Agric For 30:1–6
Mitchell CP, Ford-Robertson JB, Waters MP (1993). Establishment and monitoring of large scale trials of short rotation coppice for energy. Wood Supply research group, Department of Forestry, University of Aberdeen
Murray MB, Cannell MGR, Sheppard LJ (1986) Frost hardiness of *Nothofagus procera* and *Nothofagus obliqua* in Britain. Forestry 59:209–222
Neilan J, Thompson D (2008) *Eucalyptus* as a potential biomass species for Ireland. COFORD Connects, Reproductive Material No. 15. COFORD, Ireland, p 8
Nielsen DG, Mullenberg VL, Herms DA (2011) Interspecific variation in resistance of Asian, European and North American birches (*Betula* spp) to bronze birch borer (Coleoptera: Buprestidae). Environ Entomolog 40:648–653
Nisbet T, Thomas H, Shah N (2011) Short rotation forestry and water. In: McKay H (ed) Short rotation forestry: review of growth and environmental impacts. Forest Research Monograph 2. Forest Research, Surrey, pp 13–36
O'Reilly C, Tobin B, Farrelly N (2014) Can short rotation forestry play a role in renewable energy demands? For Eng Rev 4:32–34
OFGEM (2019a) Non-domestic renewable heat incentive. https://www.ofgem.gov.uk/environmental-programmes/non-domestic-rhi. Accessed 1 Jan 2019
OFGEM (2019b) About the FIT. https://www.ofgem.gov.uk/environmental-programmes/fit/about-fit-scheme. Accessed 1 Jan 201
Okland B, Haack RA, Wilhelmsen G (2012) Detection probability of forest pests in current inspection protocols—a case study of the bronze birch borer. Scand J For Res 27:285–297
Paton DM (1983) Physiology of frost resistance in *Eucalyptus*. In: Collogue International sur les eucalypts au froid. Nangis (France) 26–30 September 1983. AFOCEL, Nangis, France, pp 107–125
Peings Y, Cattiaux J, Douville H (2013) Evaluation and response of winter cold spells over Western Europe in CMIP5 models. Clim Dynam 41:3025–3037
Pennington HG, Bidartondo MI, Barsoum N (2011) A few exotic mycorrhizal fungi dominate eucalypts planted in England. Fungal Ecol 4:299–302
Prior J, Kendon M (2011) The UK winter of 2009/2010 compared with severe winters of the last 100 years. Weather 66:4–10
Pukkala T, Pohjonen V (1990) Yield models for *Eucalyptus globulus* fuelwood plantations in Ethiopia. Biomass 21(2):129–143
Purse J (2010) *Eucalyptus gunnii*–the pioneer Australian tree in Britain. Aust Plant 25(205):376–382
Purse JG, Leslie AD (2016a) Eucalyptus—Part 1. Species with forestry potential in the British Isles. Q J For 110:88–97
Purse J, Leslie AD (2016b) Eucalyptus—Part 2. Findings from trial plantings, and silvicultural requirements in the British Isles. Q J For 110:161–168
Purse JG, Richardson KF (2001) Short rotation single stem tree crops for energy in the UK- an examination with Eucalyptus. Aspects Appl Biol Biomass Eng Crop 65:1–8
Pyatt DG, Ray D, Fletcher J (2001) An ecological site classification for forestry in Great Britain. Forestry Commission Bulletin 124. Forestry Commission, Edinburgh
Rajapaksha NSS, Butt KR, Vanguelova EI, Moffat AJ (2013) Effects of short rotation forestry on earthworm community development in the UK. For Ecol Manag 309:96–104
Ramsay P (2004) Viable alternatives. For Mach J 9:18–19
Ranney JW, Mann LK (1994) Environmental considerations in energy crop production. Biomass Bioenerg 6:211–228
Ray D, Sing L (2006) Annex 4: climate change and species suitability analysis using ecological site classification (ESC). In: Hardcastle (2006) A review of the impacts of short-rotation forestry. LTS International. http://www.forestry.gov.uk/pdf/SRFFinalreport27Feb.pdf/$FILE/SRFFinalreport27Feb.pdf. Accessed 27 June 2007

Read DJ, Freer-Smith PH, Morison JIL, Hanley N, West CC, Snowdon P (eds) (2009) Combating climate change: a role for UK forests An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change. The Stationery Office Limited, London
SAC (2009) An assessment of the potential impact on UK agriculture and the environment of meeting renewable feedstock demands. SAC Consulting, Edinburgh
Savill P (2013) The silviculture of trees used in British forestry, 2nd edn. CABI, Oxford
Scanu B, Jones B, Webber JF (2012) A new disease of *Nothofagus* in Britain caused by *Phytophthora pseudosyringae*. New Dis Rep 25:27
Senelwa K, Sims REH (1999) Fuel characteristics of short rotation forest biomass. Biomass Bioenerg 17:127–140
Sims REH, Senelwa K, Maiava T, Bullock BT (1999) Eucalyptus species for biomass energy in New Zealand, Part II: coppice performance. Biomass Bioenerg 17:333–343
Solid Fuel Association (no date) Solid Fuel Association Guide to wood and multifuel. Solid Fuel Association. http://www.solidfuel.co.uk/pdfs/guide_to_wood_and_multifuel.pdf. Accessed 10 Aug 2015
Stokes V, Cottrell J, A'Hara S (2017) Summary report on Forest Research aspen clonal trials. Forest Research, Roslin
Straw NA, Williams DT, Kulinich O, Gninenko YI (2013) Distribution, impact and rate of spread of emerald ash borer *Agrilus planipennis* (Coleoptera: Buprestidae) in the Moscow region of Russia. Forestry 86:515–522
Sturrock RN, Frankel SJ, Brown AV, Hennon AV, Kliejunas JT, Lewis KJ, Worrall JJ, Woods AJ (2011) Climate change and forest diseases, review. Plant Pathol 60:133–149
Tabbush P, Lonsdale D (1999) Approved poplar varieties. Forestry Commission Information Note 21. Forestry Commission, Edinburgh
Teagasc (2015) Preliminary results on the physical & chemical properties of *Eucalyptus* in Ireland. http://www.teagasc.ie/forestry/docs/research/shortfor_euc_handout_DPlant_210515.pdf. Accessed 20 May 2016
Tharakan PJ, Volk TA, Abrahamson LP, White EH (2003) Energy feedstock characteristics of willow and hybrid poplar clones at harvest age. Biomass Bioenerg 25:571–580
Thomas PA (2016) Biological Flora of the British Isles: *Fraxinus excelsior*. J Ecol 104:1158–1209
Tobin B, Foreman S, O'Reilly C (2016) Short rotation forestry in Ireland—new research trials. For Eng Rev 6:28–30
Trebrown (no date) Plant hardiness zones of the British Isles. Trebrown Nurseries. http://www.trebrown.com/hrdzone.html. Accessed 4 Jan 2019
Tuley G (1980) *Nothofagus* in Britain. Forestry Commission Forest Record 122. HMSO, London
UK Plant Health Risk Register (no date) UK Plant Health Risk Register. Department for Environment Food and Rural Affairs. https://secure.fera.defra.gov.uk/phiw/riskRegister/. Accessed 24 June 2016
USDA Forest Service (no date) Wood technical fact sheet—*Nothofagus*. USDA Forest Products Laboratory. http://www.fpl.fs.fed.us/documnts/TechSheets/Chudnoff/SEAsian_Oceanic/htmlDocs_SEAsian/Nothofagusspp.html. Accessed 28 Mar 2019
Wainhouse D, Inward DJG, Denman S, Green S, Webber JF (2016) Agriculture and forestry climate change report card technical paper 7. Insect pests and pathogens of trees. http://www.nerc.ac.uk/research/partnerships/ride/lwec/report-cards/agriculture-source07/. Accessed 18 Dec 2017
Walker JCF, Butterfield BG, Harris JM, Langrish TAG, Prichard JM (2013) Primary wood processing: principles and practice. Springer, Dordrecht
Webber J, Tilbury C, Steele H, Rose D (2011) Potential impacts of pests and pathogens on short rotation forestry in Britain. In: McKay H (ed) Short rotation forestry: review of growth and environmental impacts. Forest Research Monograph 2. Forest Research, Surrey, pp 165–190
Whittaker C, Yates NE, Powers SJ, Misselbrook T, Shield I (2018) Dry matter losses and quality changes during short rotation coppice willow storage in chip or rod form. Biomass Bioenerg 112:29–36
Woodward S, Boa E (2013) Ash dieback in the UK: a wake-up call. Mol Plant Pathol 14:856–860