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Continuous cover forestry in Europe: usage and the knowledge gaps and challenges to wider adoption

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There is increasing interest across Europe in adopting forest management strategies, which promote species and structural diversity through the use of irregular silvicultural systems, an approach often described as continuous cover forestry (CCF). However, there is little information about the proportion of CCF practised across the continent or about the knowledge gaps and other obstacles that limit its use. A survey of respondents in 33 European countries sought to address these issues. The results indicated that the silvicultural systems associated with CCF were single stem, group selection and irregular shelterwood. Rotational forest management (RFM) was more frequent than CCF in about 66 per cent of countries, whereas in 25 per cent the reverse was true. We estimated that between 22 and 30 per cent of European forests are managed through CCF, although good data are lacking. The main knowledge gaps were: uncertainties arising from climate change (e.g. appropriate species choice, carbon storage in CCF), using CCF to increase forest resilience, deployment of mechanized harvesting systems, lack of knowledge about CCF amongst professional foresters and better information on economic implications of this approach. Major obstacles included: little awareness of CCF amongst forest owners, limited competence in CCF within the forestry profession and a scarcity of skilled forest workers to implement this approach, high ungulate populations damaging natural regeneration, a sawmilling sector geared to processing medium-sized logs, subsidy regimes favouring practices associated with RFM and a lack of experience in transforming plantation forests to more diverse structures. Better information on the use of different silvicultural systems is essential to allow policymakers and other stakeholders to monitor progress in diversifying forests. Establishment of a continental network of long-term operational trials (e.g. expanding the existing Association Futaie Irrégulière network) would improve professional understanding of CCF, would demonstrate this approach to forest owners and other stakeholders and could provide a valuable platform for supporting research.

Introduction

European forests cover ∼227 million ha and represent about 35 per cent of the land area of the continent (Forest Europe, 2020). Most forests are even-aged and between 20 and 80 years of age, whereas around a quarter are considered to be uneven-aged. Sixty-seven per cent of forests have two or more species and the proportion of single species stands has been decreasing over recent decades. While there is a great diversity of management objectives, forest types and species across Europe, most forests are actively managed and some 170 million ha are available for wood supply (Forest Europe, 2020). These forests also serve as important carbon stores and provide a range of ecosystem services such as biodiversity, water protection, erosion control, recreational opportunities and landscape benefits.

Many European countries are seeking to promote the practice of multifunctional or close-to nature forest management (Forest Europe, 2020, p. 13), in part to improve the provision of this wider range of ecosystem services. For example, the European Union (EU) Biodiversity Strategy recommends further development of closer-to-nature forest management as a biodiversity-friendly practice (European Commission, 2020). However, the even-aged structure of much of the forest resource across the continent (see the previous paragraph) indicates the widespread legacy of a history of rotational (or regular) forest management (RFM). This involved managing forests through silvicultural systems such as clear-cutting, seed tree and uniform or strip shelterwood (terminology after Matthews, 1989), which results in forests arranged in a series of age classes, each composed of regular stands dominated by one or very few productive tree species. Under RFM regimes, the main emphasis has been on the production of timber and the provision of other ecosystem services has largely been a 'by-product' of management

(Biber *et al*., 2015). This 'timber-centric' approach has come in for increasing criticism in recent decades, because use of RFM can be damaging to a range of services including biodiversity, water quality, carbon storage, non-timber forest products, landscape and recreational usage (Puettmann *et al*., 2015). Furthermore, the alleged superiority of the economic performance of RFM over alternative management systems has recently been seriously challenged (e.g. Knoke, 2012; Tahvonen and Rämö, 2016).

Alternative methods of forest management to RFM have been implemented in parts of Europe for well over a century (Schütz *et al*., 2012). These methods are based on a set of five silvicultural principles: partial harvesting rather than clear-felling; preferential use of natural regeneration; developing structural diversity and spatial variability within forests; fostering mixed species stands and avoidance of intensive site management practices such as soil cultivation, herbicide application and fertilizer input (Puettmann *et al*., 2015). In Europe, these silvicultural alternatives to RFM are widely known as continuous cover forestry (CCF) or as close-to-nature forestry (CNF)and are implemented using more intimate silvicultural systems such as single stem and group selection and irregular shelterwood (Schütz *et al*., 2012; Brang *et al*., 2014). In this paper, we mainly use the term CCF because its primary focus is technical and descriptive of forest structure (Pommerening and Murphy, 2004). In contrast, the term CNF can prove controversial because of varying views of the 'naturalness' of forest structures and composition produced through different silvicultural systems (e.g. Çolak *et al*., 2003; O'Hara, 2016).

Because of the importance of European forests for economic, environmental and social well-being, over the last decades attempts have been made to examine the effects of different management approaches upon the provision of a range of ecosystem services and the trade-offs that might occur. One way of facilitating this understanding is to quantify management intensity in terms of the effects upon the structure and composition of stands (Schall and Ammer, 2013). Another typology distinguished five different categories of management based on their intensity of resource manipulation and recognized CCF (termed CNF in this typology) as one of five forest management alternatives (FMAs) potentially applicable to European forests: these FMAs ranged from 'unmanaged forest nature reserve' (lowest intensity) to 'short rotation forestry' (highest intensity) (Duncker *et al*., 2012). When using this typology to assign FMAs across Europe, CCF was projected to be the preferred FMA on 18 per cent of European forests, second ranked after 'combined objective forestry' (64 per cent) (Hengeveld *et al*., 2012). The latter FMA can be interpreted as representing an intergrade between RFM and CCF, as often occurs when RFM has to be modified to take account of multifunctional objectives. Combined objective forestry differs from CCF in greater use of planting, more intensive site management, shorter rotations and implementation through a wide range of silvicultural systems (Duncker *et al*., 2012). An important feature of both classifications is that they recognize that CCF differs substantially from RFM, so that the impacts of these approaches upon forests can vary appreciably.

However, early attempts to examine the effects of greater use of 'nature-based management' were based on conventional RFM regimes modified by assuming that in the future stands will be grown on longer rotations and that the oldest stands will be unavailable for wood production (Nabuurs *et al*., 2001). More recently, similar methodologies have been used to see how different silvicultural measures could be used to help adapt European forests to climate change. Thus, in a synthesis of different European case studies, alternative measures explored for adapting forests were adjustments of RFM such as a shortening of rotation length (to reduce windthrow risk) or replacement of vulnerable tree species (Schelhaas *et al*., 2015). Such methods risk oversimplifying the diversity of management used in European forests, and it is essential to obtain a better understanding of silvicultural practices on the ground and their variation with region, ownership and institutional framework (Schelhaas *et al*., 2018). A qualitative study of three different CCF silvicultural systems (single stem selection, group selection, shelterwood) found that a group selection system was most compatible with principles of climate change adaptation, in part because the variable gap size allowed greater species diversity (Brang *et al*., 2014). Therefore, greater knowledge about the potential and practicality of the wider use of CCF for provision of ecosystem services and for adapting forests to climate change is desirable to meet the aspirations of forest policies across the continent.

Although around one-quarter of European forests are considered uneven-aged (Forest Europe, 2020), it is far from clear whether this reflects the amount of CCF being practised, since such structures could also have developed in the absence of management. No other data have been published to permit an estimate of the area of forest being managed through CCF across Europe, although some information is available for individual countries. Thus, in Slovenia where irregular silvicultural systems have been used for many decades (Diaci, 2006), over 80 per cent of forests are managed through CCF (O'Hara *et al*., 2018). At the other extreme, in Ireland in 2012 less than two per cent of forests were being managed by CCF (Vítková *et al*., 2013). There have been operational trials of CCF undertaken in various regions of the continent (e.g. attempts begun in the 1950s in Scotland to transform plantations to irregular forests; Cameron, 2019). In some cases, the proposal to introduce CCF as an alternative to RFM has been controversial and received with scepticism, as in Sweden (Axelsson and Anglestam, 2011) and Finland (Valkonen and Cheng, 2014).

In this paper, we summarize findings from a survey aiming to provide an overview of the practice of CCF across a wide range of European countries. We concentrate upon the results covering the silvicultural systems felt to be compatible with CCF, the definitions of a clear-cut, the proportion of forests being managed by different silvicultural systems and the main knowledge gaps about and obstacles to wider use of CCF.

Materials and methods

During May and June 2019 we drew up a questionnaire designed to try to obtain basic information that would provide an overview of aspects relevant to the use of CCF in Europe. Respondents were asked to reply to 12 questions, which covered: general details on the extent of forests in that country and the forest types (e.g. high forest, coppice) that were present; identification of the silvicultural systems considered to be compatible with CCF distinguishing between single stem selection, group selection, irregular, group and uniform shelterwood (terminology

Table 1 List of European countries providing replies to the questionnaire

Albania	Denmark	Greece	Lithuania	Portugal	Sweden
Austria	Estonia	Hungary	Montenegro	Romania	Switzerland
Belgium[1]	Finland	Ireland[3]	The Netherlands	Serbia[4]	Ukraine
Bosnia and Herzegovina	France	Italy	North Macedonia	Slovakia	
Croatia	Great Britain[2]	Kosovo	Norway	Slovenia	
Czech Republic	Germany	Latvia	Poland	Spain	

[1]The results from Belgium are primarily based on information for Wallonia; [2]The respondent for Great Britain was the CCF Group (www.ccfg.org.uk), which only covers England, Scotland and Wales. For Northern Ireland see note 3. [3]The respondent for Ireland was ProSilva Ireland (prosilvaireland.com), which also contains members from Northern Ireland. [4]No reply was obtained direct from Serbia, but key information was abstracted from existing publications (e.g. Diaci *et al*., 2012) or from personal contacts.

followed Matthews, 1989); whether and how a clear-cut coupe was defined in that country; the proportion of forests being managed by different silvicultural systems in 2019 and an estimate of how that had changed over the last 30 years; the road density that was found in forests; who was responsible for the marking of trees (e.g. forest worker, forester, machine operator) and whether this differed between CCF and RFM; a list of the five most important knowledge gaps about CCF in that country; and the five main obstacles to further use of this approach. Respondents were asked to provide source references for their replies wherever this was possible. A copy of the questionnaire can be found in the Supplementary data 1.

The questionnaire was circulated to an organization or group that was affiliated to ProSilva in an individual country or to personal contacts in that country if no affiliated group existed. ProSilva (https://www.prosilva.org/) is a European federation of foresters who advocate forest management based on natural processes (ProSilva, 2012). The original aim of our survey had been to collate replies only up to the end of August 2019, but an incomplete response and the need to check details of individual replies meant that we extended the deadline until the end of December 2019. Returns were obtained from 33 countries across Europe (Table 1) with only a very few (e.g. Bulgaria, Luxembourg) not responding. In one or two cases more than one reply was received from a country and in those instances we amalgamated the replies into a single return. In a few cases, the reply received was incomplete or did not cover the whole of a country (e.g. a return for Great Britain rather than for the UK).

We used a two-stage process when evaluating country replies to the questions enquiring about the main knowledge gaps about CCF and the major obstacles to wider uptake of this approach. We first combined replies that seemed to address similar issues and then tried to group these combined replies (called 'reply groups' in the remainder of this paper) into categories that constrain global use of silvicultural alternatives to even-aged forestry (Puettmann *et al*., 2015). These constraints were: ecological, economic, logistical and administrative, informational and educational, and cultural and historical.

Results

Silvicultural systems compatible with CCF

Nearly all respondents were able to state those silvicultural systems that were considered compatible with CCF in their country (Table 2), apart from one country where CCF was too new to permit a reply. Single stem and group selection were the systems felt most suitable for CCF (i.e. accepted in >90 per cent of replies), with a rather smaller proportion considering irregular shelterwood to be acceptable. Around half of respondents would also accept group or uniform shelterwood systems, but several noted that this would only apply during the transformation from RFM to CCF (e.g. Great Britain, Hungary). Other approaches mentioned included coppice systems (Greece) and mountain selection system (Norway), while the Slovenian free style silviculture combines elements of selection and irregular shelterwood systems depending upon site conditions and stand structure (Boncina, 2011).

Definition of a clear-cut coupe

There was a range of replies to this question (Table 3). In some countries (e.g. Albania, Greece, the Netherlands) there appeared to be no formal or legal definition of the size of a coupe, which would be classed as a clear-cut. However, often in such cases there was an upper limit set on the maximum permitted size of a clear-cut, for example between 3 and 5 ha in Romania. A few countries (e.g. Montenegro, Slovenia) had an explicit prohibition of clear-felling. Most respondents considered that the critical size separating the felling of a group of trees as part of CCF from a clear-felled coupe would be between 0.1 and 0.5 ha. In some countries (e.g. Denmark, Slovakia and Switzerland) the definition was not in terms of area but rather in terms of gap size in relation to adjoining tree height (e.g. gap width not more than two tree heights).

Proportion of forests managed by different silvicultural systems

This question proved to be one of the most difficult ones for respondents to answer. Only 18 countries (Table 4) were able to provide a referenced estimate of the area of forest managed by different silvicultural systems: some of these replies were based on extrapolations from National Forest Inventory (NFI) data (e.g. Italy). In a number of Nordic countries (e.g. Finland, Estonia) no figures on the areas managed by different systems were available. Here replies were based on the proportion of annual fellings originating from different silvicultural systems. In several countries (e.g. Great Britain, Switzerland) no formal data were available, but respondents provided a personal estimate of the proportion being managed by different systems. Lastly, two

Table 2 Silvicultural systems considered to be compatible with CCF (per cent of replies)

Silvicultural system	Single stem selection	Group selection	Irregular shelterwood	Group shelterwood	Uniform shelterwood	Other
Per cent	97	94	79	55	45	15

Table 3 Critical size of a coupe which separated a CCF felling from a clear-fell

Size category (ha)	No formal definition	No clear-cuts allowed	≤0.5 ha
Number of countries	12	2	19

countries (Austria, Kosovo) had no formal data and no estimates were provided.

RFM was a more frequent management approach than CCF in 66 per cent of European countries (Table 4; Figure 1), with clear-felling and uniform shelterwood being the commonest systems that were used in RFM. Silvicultural systems associated with CCF were a higher proportion than RFM in 25 per cent of countries: these were mainly located in central and south-eastern Europe. Fifteen countries reported appreciable proportions of coppice stands or plantations being transformed to CCF (e.g. Denmark, Greece and the Netherlands). In most countries, there was evidence of a mix of RFM and CCF approaches with a range of silvicultural systems being used. Perhaps, the main exception was in those Scandinavian and Baltic countries where acceptance of CCF and its adoption was very recent.

Respondents generally found it difficult to provide accurate data about changes in the proportion of different silvicultural systems over the last 30 years with over 40 per cent being unable to provide any figures. Of those who provided estimates, 36 per cent felt that there had been an increase in the use of CCF, 15 per cent thought there had been little if any change, whereas the remainder (primarily Estonia and Poland) considered there had been an increase in RFM. In Poland, this was a consequence of damage by wind, insects, fire and drought (M. Pach, personal communication) There were other changes within categories in individual countries such as a decline in seed tree systems in Finland in favour of clear-felling or a decline in single stem selection in Slovenia in favour of the use of an irregular shelterwood system.

Estimate of the overall proportion of European forests managed by CCF

We combined the individual country estimates of the proportion of forests managed through silvicultural systems either associated with RFM or with CCF (Table 4) with other data for the amount of high forest in each country (Forest Europe 2020, Annex 8, Table 28). This allowed us to calculate that the overall area of forests managed by CCF in 31 European countries (i.e. excluding Austria and Kosovo for which we had no returns) was ∼39 million ha or 22 per cent of the high forest area. If we ignored Finland and Sweden, where CCF has only been accepted as a management approach in the last decade, then the proportion of European forests managed by CCF increased to ∼30 per cent.

Main knowledge gaps and obstacles limiting the uptake of CCF

Replies to these questions were received from all countries except Serbia, and these listed 142 knowledge gaps and 146 obstacles. However, a preliminary examination of the replies suggested that two that were listed as knowledge gaps ('a lack of skilled workers' and 'forest owners with little knowledge or interest') were better classed as obstacles. Similarly, comments that included 'climate change' as an obstacle to wider uptake of CCF were felt to be referring to knowledge gaps. As a result of these adjustments, the modified figures were 125 knowledge gaps and 163 obstacles identified by the respondents. For each of these challenges, we ranked the reply groups (see above) in decreasing order of importance (Table 5) and have only listed those groups whose combined incidence amounted to 75 per cent or more of the total.

Knowledge gaps

The two main knowledge gaps identified both fell into the 'ecological' category and were responsible for over 45 per cent of issues, whereas the other three gaps were in different categories. The first knowledge gap dealt with a range of uncertainties arising from climate change including identifying suitable species and provenances for use in a future climate and the dynamics of carbon storage under CCF management. The second reflected worries about how best to use CCF to increase the ability of forests to recover from the impacts both of climate change and from the hazards posed by pests and pathogens. The third and fourth limitations had similar rankings, involving the use of mechanized harvesting systems in CCF forests and the need for increasing knowledge about CCF amongst professional foresters. Both tended to be commoner amongst replies from countries where CCF had only recently been accepted and the forest sector was based on even-aged forests managed through RFM (e.g. Finland, Spain). The last important knowledge gap concerned an absence of good information on the economics of CCF and on supporting information on increment, yield and wood properties. Again this issue tended to be raised by respondents from countries where RFM was the main management approach.

Table 4 Percentage use of various silvicultural systems in high forests estimated for different European countries

Country	RFM – silvicultural systems					CCF – silvicultural systems				Notes (with source year for data if known)
	Clear-felling	Uniform shelterwood	Strip shelterwood	Seed tree	Other	Single stem selection	Group selection	Irregular shelterwood	Undergoing transforma-tion to CCF	
Albania		100								Data derived from NFI (2004)
Austria	ND					ND				
Belgium	55					45				Estimate (G. Ligot and C Sanchez, personal communication)
Bosnia and Herzegovina						90	10			Z. Govedar, personal communication
Croatia	4	48				14	<1	30	4	General Forest Management Plan (2016)
Czech Republic	75	18	1			<1	<1	1	4	NFI data supplemented by national questionnaire (2017)
Denmark	76	7	5	<1		<1	2	<1	10	Estimate based on NFI data (2017)
Estonia	90	9				<1				Based on fellings recorded in Yearbook Forest 2017. No distinction between different shelterwood systems
Finland	80			17		1	1		1	Based on official statistics for fellings (2017)
France	75					25				Estimate (ProSilva France 2019)
Germany	20	40			10	30				Estimate (P. Spathelf, personal communication)
Great Britain	84	1				1	2	2	10	Estimate (Continuous Cover Forestry Group 2019)
Greece					<1	18		29	53	Derived from NFI (1992)
Hungary	64	29				2			5	Derived from official data (2019)
Ireland	98	<1				1		<1		Based on 2012 data for the Republic of Ireland (Vítková *et al.*, 2013)
Italy		43				37		15	5	Derived from NFI (2005). No distinction between single stem and group selection
Kosovo	ND					ND				
Latvia	92			1		7				Based on official information on final fellings and on choice of management regime (2018)
Lithuania	95		5							Based on felling areas in state forests (2016)
Montenegro	<1					84	10		6	Z. Govedar, personal communication
The Netherlands	56	13				2	3	6	20	Derived from NFI report of Schelhaas *et al.* (2014)
North Macedonia	64					9	16	11		Information from national forests enterprise (2018)
Norway	74	1		18	1	1	4	1		Other is the 'mountain selection system'. Derived from 2013 data: https://www.nibio.no/tema/skog/skogbehandling-og-skogskjotsel/foryngelseshogst
Poland	64	30				6				Derived from 'Forests in Poland' 2018 and Statistical Yearbook of Forestry 2020. Only clear-fell identified and an arbitrary division of remainder into even-aged and CCF
Portugal	79	18	<1			3				NFI (2010)
Romania	3	2			41	3		51		Derived from Statistical Yearbook of Romania, 2017. Other is group shelterwood
Serbia		91				<1	1	8		Diaci *et al.*, 2012
Slovakia	16	76	1			1	1	5		Estimate – M. Saniga and R. Bruchánik, personal communication
Slovenia	<1					5		85	10	Yearly report of Forest Service (2018)
Spain	85					15				Estimate since no official data – G. Miaillier, personal communication
Sweden	89			11		<1	<1			Based on Swedish Forest Agency data on final fellings (2017)
Switzerland						13	7	73	7	Estimate (P. Brang, personal communication)
Ukraine	80	17				<1	<1	1	1	V. Lavnyy, personal communication

Percentages are based on data sources of varying quality – see notes column in the table and the text of the main paper for more information. Where NFI and a date is given, it refers to the National Forest Inventory of that country for that year.

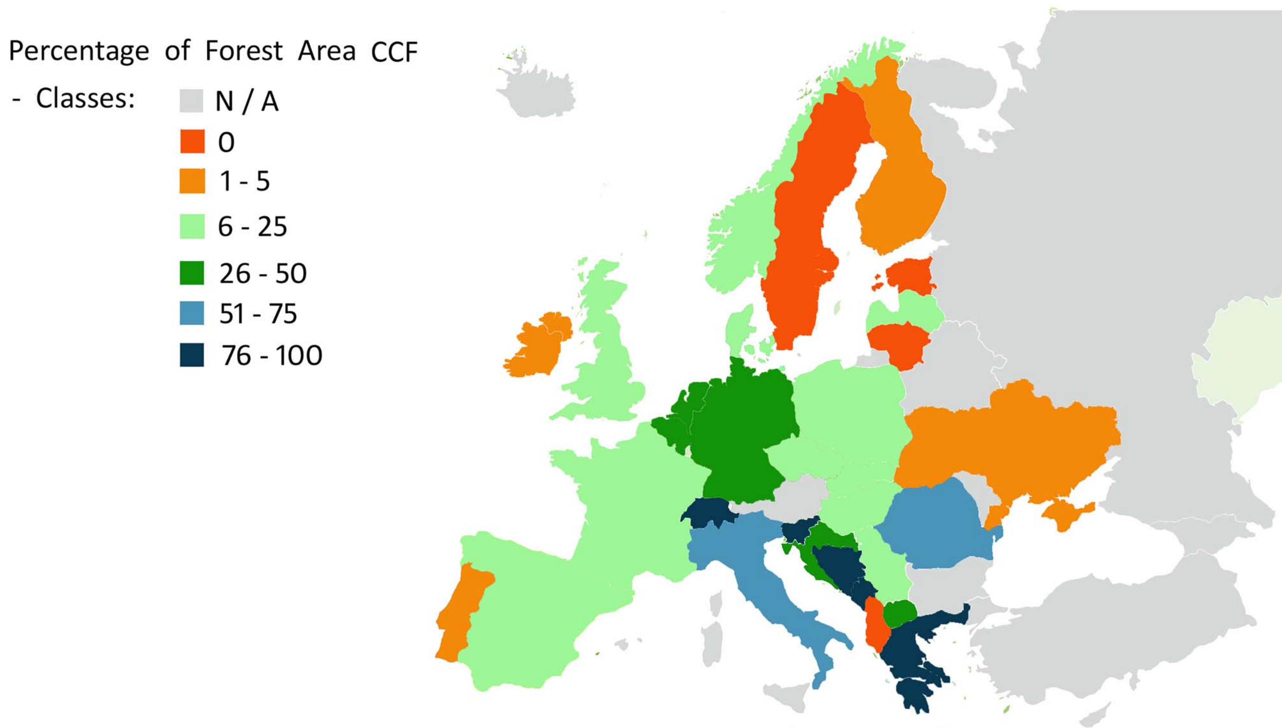

Figure 1 Percentage of forest area managed by CCF by country across Europe (see Table 4 for a detailed breakdown and notes on the different data sources used).

Obstacles

By contrast, there was a more even spread of issues relating to obstacles to uptake of CCF raised by respondents so that six reply groups could be identified (Table 5). The most important obstacles appeared to have a substantial informational/educational element. The first obstacle involved a lack of awareness of CCF amongst forests owners and other senior stakeholders, together with inadequate knowledge transfer to such people. This could be linked to the second ranked obstacle, which was a lack of competence in implementing CCF amongst forestry professionals, augmented by a shortage of skilled forest workers to implement CCF regimes. An important constraint was the problem of insufficient natural regeneration due to heavy browsing pressure from deer and other mammals. While the consequences of this problem fell into the ecological category, finding a solution could require changes both to the measures used to control ungulates and to legislation affecting the management of wild game, and thus, there was a logistical and administrative aspect to be considered. A similar ranking was given to a group containing economic factors such as difficult timber markets, declining prices paid for the large dimension logs often produced under CCF systems and the costs perceived to be associated with the transformation of even-aged stands to CCF. There was a widespread perception that the subsidy schemes and tax regimes that applied to private forests in the various countries were designed primarily for RFM (e.g. grants given for planting that provide short-term outcomes rather than for the longer term processes associated with natural regeneration). Lastly, a number of respondents noted the challenges associated with introducing CCF into planted forests that often lack species and structural diversity. This tended to be an issue that was raised by respondents from countries with substantial plantation resources (Great Britain, Ireland) or where the practices of RFM had tended to homogenize forests (Finland).

Discussion

Appropriate silvicultural systems and coupe size

It is evident from the responses summarized in Table 2 that most countries consider single stem and group selection as being the silvicultural systems most compatible with the principles of CCF, as previously indicated by other authors (e.g. Schütz *et al*., 2012; Brang *et al*., 2014). The acceptability of shelterwood systems is less clear with the greater heterogeneity provided by an irregular shelterwood generally deemed to be more appropriate for CCF than the spatial regularity that can characterize a uniform shelterwood. However, even a uniform shelterwood system can be acceptable when implemented as part of the process of transforming a stand from RFM to CCF, since the occurrence of natural regeneration and retention of some overstorey trees provide greater structural diversity than the open ground conditions characteristic of clear-felled sites being replanted under RFM (Schütz *et al*., 2012). The desirability of applying a mix of

Table 5 A summaryof the main knowledge gaps affecting the uptake of CCF across Europe and the major obstacles to its wider use, grouped by the categories of constraint identified by Puettmann *et al.* (2015).

Knowledge gaps			Obstacles		
Type	Per cent of total	Category of constraint	Type	Per cen t of total	Category of constraint
1. Applying CCF in an era of climate change (e.g. selecting climate adapted species; managing carbon stores)	31	Ecological	A. Limited knowledge about CCF amongst owners and poor knowledge transfer	18	Informational/ educational
2. Resistance and resilience of CCF stands compared with even-aged ones	15	Ecological	B. Lack of CCF skills in profession and amongst forest workers	15	Cultural/historical (also information-al/educational)
3. Using mechanized harvesting systems in CCF	14	Logistical/ administrative	C. Browsing pressure from deer and other animals	13	Ecological (also logistical/adminis-trative)
4. Limited professional awareness of CCF including lack of examples	14	Informational/ educational	D. Economic considerations such as low timber prices for larger logs produced in CCF	13	Economic
5. Poor data on the economic aspects of CCF including timber quality and yields	10	Economic	E. Grant and tax schemes that are unsympathetic to CCF	12	Logistical/ administrative
			F. Introducing CCF into even-aged forests with little species or structural diversity	8	Ecological (also informational/edu-cational)

CCF silvicultural systems that are sensitive to site, species requirements and stand structure is increasingly recognized as a way of increasing forest resilience and adaptation to climate change (Boncina, 2011; Schütz *et al.*, 2016). This practice also provides for greater species diversity and structural heterogeneity at a landscape scale and counters some criticisms of CNF (O'Hara, 2016).

While there was only a partial response to the query about the size of area that would be identified as a clear-cut (Table 3), the replies made it clear that CCF is identified with small scale coupes <0.5 ha in size, even if there may be several of these within a CCF stand. This contrasts with the area of clear-felled coupes in RFM, which may range between 5 and 20 ha or more, depending on the region and whether clear-felling of larger areas is permitted. This small scale of CCF working is in line with the principle of partial harvesting of timber that is one of the characteristics of alternative silvicultural systems to RFM (Puettmann *et al.*, 2015). However, the smaller size of acceptable coupe (0.1 ha) reported from some countries could cause the loss of light-demanding species because of an unfavourable growing environment (Bauhus *et al.*, 2013; Kern *et al.*, 2017). This risk may be higher in countries where the most important commercial tree species are either light demanding or intermediate in terms of shade tolerance, as is the case in Great Britain (Malcolm *et al.*, 2001).

Proportion of forests managed by CCF

A striking feature revealed by the questionnaire was the almost total absence of definitive and referenced data on the proportion of forests being managed by different silvicultural systems (Table 4). CCF was the commonest in those regions and countries of central Europe (e.g. Switzerland, southern Germany and eastern France) where the intimate silvicultural systems associated with CCF were first formalized (Schütz *et al.*, 2012). The approach was also prominent in some countries of southern and south-eastern Europe with a tradition of exchange of silvicultural knowledge with central Europe (O'Hara *et al.*, 2018). The responses indicated a general increase in the amount of CCF practised in Europe over the last 30 years (cf. Schütz *et al.*, 2012).

While allowing for inevitable uncertainty due to the rough estimates provided, it would appear that the proportion of Europe's forests being managed using a CCF approach ranges from just under one-quarter to nearly one-third of the total forest area. This figure is higher than the 18 per cent of CNF calculated by Hengeveld *et al.* (2012) using a FMA framework, but the difference may reflect that the 'combined objective forestry' FMA category could include stands undergoing transformation to CNF (Duncker *et al.*, 2012). Our estimate of the area managed by CCF is similar to the figure of one-quarter of forests identified as 'uneven-aged' by Forest Europe (2020). However, that the latter is based upon forest inventories whose information only describes current structures and does not capture how forests are actually managed (Coll *et al*., 2018). This absence of detailed figures about silvicultural practices is regrettable given the widespread aspiration in country forest policies to increase the amount of CCF management (Forest Europe, 2020). Designing inventories that provide better information on silvicultural practices and forest management is essential to provide a baseline against which changes can be measured (Schelhaas *et al*., 2018).

Knowledge gaps

Uncertainties about the best way to apply CCF in a time of climate change were by far the largest knowledge gaps identified (Table 5; #1 and 2). Similar results were found in a survey of forest managers' knowledge about mixed forests in Europe (Coll *et al*., 2018). A long-standing argument in favour of greater use of CCF has been that the complex stands developed through use of irregular silvicultural systems provide a means of increasing forest resilience to major disturbances that can seriously damage forests under RFM (Otto, 2000; O'Hara and Ramage, 2013). However, there has also been concern that unquestioning application of a particular silvicultural system (e.g. single stem selection) could result in structures that were vulnerable to changing disturbance regimes (North and Keeton, 2008; Palik *et al*., 2021). This criticism can also be levied at tendencies to apply RFM (e.g. clear-felling, fostering of single species stands) rigidly as a 'default option' irrespective of site and stand structure. First principles suggest that using a combination of site-adapted irregular silvicultural systems as in 'free style' silviculture (Boncina, 2011) together with adaptive management informed by periodic monitoring is a sensible way of providing the guidance necessary to encourage managers about the beneficial role of CCF as a means of increasing forest resilience in an era of climate change.

The three other important knowledge gaps identified through our questionnaire are more related to operational implications of the CCF approach (Table 5: #3–5).The third gap relates to the use of mechanized harvesting systems in CCF forests reflecting the shift away from traditional motor manual felling systems (e.g. in Sweden: Nordjfell *et al*., 2010). This trend can be managed, provided that adequate training is given to operators in CCF harvesting, that this training is consolidated through operational practice and that systematic racking systems are installed, which allow access for harvesting machines within stands without damage to the retained matrix (Purser *et al*., 2015). The fifth gap is a difficulty in finding comprehensive economic data on experience with CCF including impacts on timber quality and yields. Economic modelling has suggested that CCF may be particularly attractive for risk-averse forest owners (Roessiger *et al*., 2011). Recent studies have shown how the relative profitability of CCF against RFM can be heavily influenced by savings on establishment costs if natural regeneration is successful (Davies and Kerr, 2015; Peura *et al*., 2018). A higher sawlog output from the large dimension timber that is produced by CCF (Schütz *et al*., 2012) can also make this approach more profitable, although realization of this potential will be influenced by regional timber markets, by the timber properties of different species and if larger trees prove more vulnerable to an increased occurrence of droughts.

One important way of providing information about practical aspects such as use of mechanized harvesting systems or the economic implications of transformation to CCF is to install large-scale trials, which can provide the desired operational data. A larger scale is desirable to ensure that the landscape implications of use of a CCF approach can be established (e.g. the DIST-DYN project in Finland; Koivula *et al*., 2014). The results from operational trials can be used to complement those obtained from smaller plots (e.g. Marteloscopes, Krumm *et al*., 2019). The resulting knowledge can inform professional foresters, students and other interested parties about ways of implementing a CCF approach in a given country and in a particular forest type and thus can help to address the fourth knowledge gap (Table 5). The major European network of larger sites relevant to CCF is the 130 reference stands of the Association Futaie Irrégulière (AFI) located across eight countries of western and central Europe (https://www.prosilva.org/activities/afi/). Otherwise, operational trials tend to be at a country or regional level and often have been developed without consistent protocols. For example, Wilson (2013) found ∼150 examples of CCF being implemented across Great Britain but noted a lack of monitoring of the results. Because of the potential importance of CCF as a means of adapting forests to climate change, arguably greater emphasis should be given to developing a continental network of long-term trials to exchange information along the lines of the Adaptive Silviculture for Climate Change project in the US (Nagel *et al*., 2017), possibly by expanding the existing AFI network.

Major obstacles

Arguably, the two highest ranked obstacles to change (Table 5, #A and B) are closely related. Thus, limited knowledge of CCF amongst private owners (#A) can be linked to the lack of CCF skills amongst foresters and forest workers (#B), whereas poor knowledge transfer (presumably from foresters to owners) may also indicate a lack of understanding and training in CCF being reflected in inadequate advice. However, the issue of dealing with forests owners with an apparent lack of knowledge about and motivation for forest management is not unique to CCF, since there is a long-standing and widespread concern amongst foresters in different countries that private owners are not managing their forests adequately (e.g. Lawrence and Dandy, 2014, for a discussion of problems in the UK). It is likely that owners' motivation and interest will be influenced by the particular circumstances of the forest or region in which this is located. Thus, there were appreciable differences between 10 European case study regions in the readiness of forest managers to take measures to adapt forests to climate change (Bouriaud *et al*., 2015). However, overcoming these linked obstacles will require organizational leadership within the forestry sector in different countries to facilitate the trialling of alternative silvicultural approaches (Puettmann *et al*., 2015). Without support for attempts to try new approaches, there is a risk that the limited silvicultural innovation underway in different countries is hampered (Lawrence, 2017) and that CCF is felt to be risky. Successful implementation of CCF also requires a workforce trained in the skills needed to undertake stand tending or harvesting operations and equipped with appropriate tools and machinery (Puettmann *et al*., 2015). There is need to share existing knowledge and practice about CCF in Europe to provide support and guidance to owners and foresters interested in using this approach.

Because the implementation of irregular silvicultural systems generally assumes the establishment of cohorts of natural regeneration that are widely dispersed through a forest, the success or failure of the CCF approach can be critically affected by browsing pressure from deer and other animals (Table 5, #C). Problems with excessive deer populations or livestock grazing limiting regeneration success in forests have been reported for decades (Tremblay *et al*., 2006; Carvalho, 2018; Ramirez *et al*., 2018). This issue is often considered primarily as an ecological constraint, involving discussions about how best to assess browsing damage and the interaction with silvicultural system and forest type (e.g. Reimoser *et al*., 1999) together with better understanding of deer population dynamics. However, the practicality of achieving effective ungulate population control depends upon achieving stakeholder agreement on integrated game or livestock management measures. For example, a recent review of deer management in Scotland has recommended a fresh approach, including revised legislative powers, to bring deer populations under control (Deer Management Group, 2019) and similar conclusions have been reached in Germany (Jordan-Fragstein and Müller, 2019). Thus, ungulate management can also be classed as a logistical or administrative constraint upon the implementation of CCF.

Wider uptake of CCF requires that this approach is financially attractive to forest owners (Table 5, #D), and, as noted above, the production of large dimension timber has traditionally been seen as one of the monetary benefits of irregular silvicultural systems, especially from single stem selection (Schütz *et al*., 2012). However, parts of the conifer sawmilling industry in Europe have concentrated upon the processing of medium-sized trees with target log diameters of 30–50 cm. These systems are not adapted to handling larger logs >60 cm, which can mean that no price premium is paid for such material unless it involves species of desired timber properties like Douglas fir (Davies and Kerr, 2015). Such problems can be overcome if national forecasts of timber production are modified to predict anticipated production of large dimension conifer logs over the next 10–20 years or indeed other changes in timber supply consequent upon wider adoption of CCF. These projections can give sawmills an indication of likely timber flows and provide time for investment in lines specifically designed for larger logs. In addition, everything else being equal the conversion efficiency at the sawmill should be greater with larger logs (Carvalho, 2018).

A problem that has been noted on several occasions (e.g. Wilson, 2013) is that the national financial support available to private landowners and foresters from forestry grant schemes has generally been designed to support activities characteristic of RFM as compensation for incurred costs (e.g. planting, site cultivation) (Table 5, #E). The success of these activities can usually be evaluated within 3–5 years, which means that they can be easily accommodated within the framework of payments made under the EU's Common Agricultural Policy (B. Callaghan, Scottish Forestry, personal communication). In contrast, management costs that can be directly reimbursed are often minimal in CCF. Furthermore, management activities undertaken under CCF such as thinning to promote the development of natural regeneration can take a decade or more for their success or failure to be evident. For this reason, financial support for implementing CCF has often been confined to capital grants for measures such as improving infrastructure for access within forests (Puettmann *et al*., 2015). However, a recent scheme in Ireland provides for three-staged payments of 750€ ha^{-1} over a 12-year period to support a range of management activities associated with CCF such as management planning, tree marking and improvement thinnings and promotion of natural regeneration, all under the supervision of an approved forester skilled in CCF (Anonymous, 2019). Similar schemes exist in Switzerland and Germany where subsidies are paid according to achieved goals (e.g. share of oak established in regeneration) and not according to silvicultural operations (planting of oak). Given that one reason for increasing the proportion of forests managed by CCF is to enhance the provision of a range of ecosystem services, then consideration of paying forest owners and managers for achieving a desired silvicultural objective through CCF could be explored further (e.g. UNECE, 2014).

The last major obstacle identified (Table 5, #F) refers to the problem of transforming homogeneous even-aged forests to CCF, which can be a particular problem in countries such as Ireland, the UK, Belgium and Denmark where plantations comprise an appreciable proportion of the forest resource (Forest Europe, 2020). Many of these planted forests are dominated by non-native tree species and have been intensively managed through RFM, resulting in a lack of older and unmanaged stands to provide guidance on likely stand dynamics under a CCF approach (cf. Brang, 2005 for a discussion of the utility of virgin forests for guiding CNF management in central Europe). This obstacle is also apparent in countries like Finland and Sweden where intensive RFM has transformed the majority of forests into uniform even-aged stands with plantation characteristics. Some information on appropriate silvicultural systems for transformation to CCF can be obtained from understanding of species ecophysiology, supplemented by research findings and operational trials (Malcolm *et al*., 2001; Schütz, 2001; Mason, 2015). The systems most appropriate for the transformation of regular stands can differ from those that will be used in an irregular one, exemplified by increasing recognition of the benefits provided by the retained overstorey trees found in shelterwood or variable retention systems for long-term structural diversity (Schutz *et al*., 2012; Beese *et al*., 2019). Attempts made to evaluate patterns of natural disturbance in analogous climates to guide silvicultural practice have shown that the patch clear-felling systems widely used in British conifer forests 'have no apparent parallel in comparable natural forests' (Quine *et al*., 1999). Therefore, transformation to CCF can be difficult because of a lack of clarity about desired future structural and species composition. One way of overcoming this problem is through the use of Forest Development Types, which describe the long-term forest composition and structure appropriate for a specific site and climate, and then outline the silvicultural actions required to guide actual forest stands in the desired direction (Larsen and Nielsen, 2007).

Conclusions

This paper indicates that silvicultural systems associated with CCF are being used for managing forests in many European countries. The practice of CCF appears to be increasing in line with the widespread policy aspirations to expand the extent of multifunctional management of European forests (Forest Europe, 2020; Gresh and Courter, 2021). However, in most countries a lack of NFI data on silvicultural practices mean that it is difficult to state the proportion of forests being managed by CCF or to evaluate silvicultural trends over time. Better national figures on silvicultural regimes are urgently needed because the development of irregular mixed forests through CCF is recognized as an important means of adapting forests to the challenges arising from climate change (Brang *et al*., 2014).

Our findings also highlight the apparent hesitance of some professional foresters to consider the feasibility of a CCF approach, further supporting the view that forestry traditions and culture can be a major factor influencing the adoption of alternative silvicultural approaches (Puettmann *et al*., 2015; O'Hara *et al*., 2018). Overcoming such misgivings seems central to achieving wider use of CCF and requires educating professionals about the effectiveness of CCF in delivering the objectives of modern multifunctional forestry and persuading forest owners and other rural stakeholders of the desirability of this approach. Measures that can be taken to increase knowledge about CCF and facilitate its wider uptake include the establishment of a European network of operational trials to inform managers about feasible practices. If properly documented and with the results widely available (e.g. through on-line platforms), these trials can also serve to illustrate the utility of CCF in increasing forest resilience to climate change and other hazards. Experience in these trials could be used to design financial mechanisms that would help encourage private owners to adopt CCF. The trials should also provide an essential infrastructure for the supporting research that is still required to explore the impacts of greater use of CCF upon the adaptation of European forests to climate change and the effect upon the delivery of various ecosystem services across the different regions and forest types of the continent.

Supplementary material

Supplementary data are available at *Forestry* online.

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References

Anonymous 2019 *Element 2 – Woodland Improvement Scheme: Continuous Cover Forestry*. Department of Agriculture, Food and the Marine, p. 28. https://www.agriculture.gov.ie/media/migration/forestry/grantandpremiumschemes/2019/WISCCFVer6120319.pdf (accessed on 2 June 2020)

Axelsson, R. and Anglestam, P. 2011 Uneven-aged forest management in boreal Sweden: local forestry stakeholders' perceptions of different sustainability dimensions. *Forestry* **84**, 567–579.

Bauhus, J., Puettmann, K.J. and Kuhne, C. 2013 Close-to-nature forest management in Europe: does it support complexity and adaptability of forest ecosystems. In *Managing Forests as Complex Adaptive Systems*. C., Messier, K.J., Puettmann, K.D., Coates (eds.). Routledge, pp. 187–213.

Beese, W.J., Deal, J., Dunsworth, G., Mitchell, S.J. and Philpott, T.J. 2019 Two decades of variable retention in British Columbia: a review of its implementation and effectiveness for biodiversity conservation. *Ecol. Processes* **8**, 33.

Biber, P., Borges, J.G., Mosshammer, R., Barreiro, S., Botequim, B., Brodrechtova, Y. *et al*. 2015 How sensitive are ecosystem services in European forest landscapes to silvicultural treatment? *Forests* **6**, 1666–1695.

Boncina, A. 2011 History, current status and future prospects of uneven-aged forest management in the Dinaric region: an overview. *Forestry* **84**, 467–478.

Bouriaud, L., Marzano, M., Lexer, M., Nichiforel, L., Reyer, C., Temperli, C. *et al*. 2015 Institutional factors and opportunities for adapting European forest management to climate change. *Reg. Environ. Change* **15**, 1595–1609.

Brang, P. 2005 Virgin forests as a knowledge source for central European silviculture: reality or myth? *For. Snow Landsc. Res.* **79**, 19–32.

Brang, P., Spathelf, P., Larsen, J.B., Bauhus, J., Boncina, A., Chauvin, C. *et al*. 2014 Suitability of close-to-nature silviculture for adapting temperate European forests to climate change. *Forestry* **87**, 492–503.

Cameron, A.D. 2019 Creating a permanent irregular forest: a review of the transformation at Faskally Forest, Perthshire. *Scott. Forestry* **73**, 30–38.

Carvalho, J. 2018 *Close-to-Nature Silviculture – Reconciling Economy and Ecology for a Multifunctional, Profitable and Sustainable Silviculture*. Quantica–Engebook, (in Portugese).

Çolak, A., Rotherham, I. and Çalikoglu, M. 2003 Combining 'naturalness concepts' with close-to-nature silviculture. *Forstwissenschaftliches Centralblatt* **122**, 421–431.

Coll, L., Ameztegui, A., Collet, C., Löf, M., Mason, B., Pach, M. *et al*. 2018 Knowledge gaps about mixed forests: what do European forest managers want to know and what answers can science provide? *For. Ecol. Manage.* **407**, 106–115.

Davies, O. and Kerr, G. 2015 Comparing the costs and revenues of transformation to continuous cover forestry for Sitka spruce in Great Britain. *Forests* **6**, 2424–2449.

Deer Management Group 2019. *The Management of Wild Deer in Scotland*. https://www.gov.scot/publications/management-wild-deer-scotland/ (accessed on 2 June 2020).

Diaci, J. 2006 Nature-based silviculture in Slovenia: origins, development and future trends. In: *Nature based forestry in Central Europe: alternatives to industrial forestry and strict preservation*. J. Diaci (ed.). *Studia Forestalia Slovenica* 126. Biotechnical Faculty, University of Ljubljana, Slovenia. pp. 126–178.

Diaci, J., Govedar, Z., Krstić, M. and Motta, R. 2012 Importance and perspectives of silviculture for the science and practice of forestry. In *Forestry Science and Practice for the Purpose of Sustainable Development of Forestry*. Z., Govedar, V., Dukić (eds.), pp. 23–40.

Duncker, P.S., Barreiro, S.M., Hengeveld, G.M., Lind, T., Mason, W.L., Ambrozy, S. *et al.* 2012 Classification of forest management approaches: a new conceptual framework and its applicability to European forestry. *Ecol. Soc.* **17**, 51.

European Commission. 2020 *EU Biodiversity Strategy for 2030: Bringing Nature Back Into our Lives*. https://ec.europa.eu/environment/strategy/biodiversity-strategy-2030_en (accessed on 9 June 2021).

Forest Europe. 2020 *State of Europe's Forests 2020*. https://foresteurope.org/state-europes-forests-2020/ (accessed on 15 February 2021).

Gresh, J.M. and Courter, J.R. 2021 In pursuit of ecological forestry: historical barriers and ecosystem implications. *Front. For. Glob. Change* **4**, 571438. 10.3389/ffgc.2021.571438.

Hengeveld, G.M., Nabuurs, G.-J., Didion, M., van den Wyngaert, I., Clerkx, A.P.P.M. and Schelhaas, M.-J. 2012 A forest management map of European forests. *Ecol. Soc.* **17**, 53.

Jordan-Fragstein, C. and Müller, M. 2019 The BioWild project. *Deer* **19**, 16–18.

Kern, C.C., Burton, J.I., Raymond, P., D'Amato, A.W., Keeton, W.S., Royo, A.A. *et al.* 2017 Challenges facing gap-based silviculture and possible solutions for Mesic northern forests in North America. *Forestry* **90**, 4–17.

Knoke, T. 2012 The economics of continuous cover forestry. In *Continuous Cover Forestry*. T., Pukkala, K., von Gadow (eds.). Springer Science, pp. 167–193.

Koivula, M., Kuuluvainen, T., Hallman, E., Kouki, J., Siitonen, J. and Valkonen, S. 2014 Forest management inspired by natural disturbance dynamics (DISTDYN) – a long-term research and development project in Finland. *Scand. J. For. Res.* **29**, 579–592.

Krumm, F., Lachat, T., Schuck, A., Bütler, R. and Kraus, D. 2019 Marteloscopes as training tools for the retention and conservation of habitat trees in forests. *Schweiz. Z. Forstwes.* **170**, 86–93 (in German).

Larsen, J.B. and Nielsen, A. 2007 Nature-based forest management—where are we going? Elaborating forest development types in and with practice. *For. Ecol. Manage.* **238**, 107–117.

Lawrence, A. 2017 Adapting through practice: silviculture, innovation and forest governance for the age of extreme uncertainty. *For. Policy Econ.* **79**, 50–60.

Lawrence, A. and Dandy, N. 2014 Private landowners' attitudes to planting and managing forests in the UK: what's the evidence? *Land Use Policy* **36**, 351–360.

Malcolm, D.C., Mason, W.L. and Clarke, G.C. 2001 The transformation of conifer forests in Britain – regeneration, gap size, and silvicultural system. *For. Ecol. Manage.* **151**, 7–23.

Mason, W.L. 2015 Implementing continuous cover forestry in planted forests: experience with Sitka spruce (*Picea sitchensis*) in the British Isles. *Forests* **6**, 879–902.

Matthews, J.D. 1989 *Silvicultural Systems*. Oxford University Press.

Nabuurs, G.-J., Paivinen, R. and Schanz, H. 2001 Sustainable management regimes for Europe's forests: a projection with EFISCEN until 2050. *For. Policy Econ.* **3**, 155–173.

Nagel, L.M., Palik, B.J., Battaglia, M.A., D'Amato, A.W., Guldin, J.M., Swanston, C.W. *et al.* 2017 Adaptive silviculture for climate change: a national experiment in manager-scientist partnerships to apply an adaptation framework. *J. For.* **115**, 167–178.

Nordfjell, T., Björheden, R., Thor, M. and Wästerlund, I. 2010 Changes in technical performance, mechanical availability and prices of machines used in forest operations in Sweden from 1985 to 2010. *Scand. J. For. Res.* **25**, 382–389.

North, M.P. and Keeton, W.S. 2008 Emulating natural disturbance regimes: an emerging approach for sustainable forest management. In *Patterns and Processes in Forest Landscapes*. R., Lafortezza, G., Sanesi, J., Chen, T.R., Crow (eds.). Springer, pp. 341–372.

O'Hara, K.L. 2016 What is close-to-nature silviculture in a changing world? *Forestry* **89**, 1–6.

O'Hara, K.L. and Ramage, B.S. 2013 Silviculture in an uncertain world: Utilizing multi-aged management systems to integrate disturbance. *Forestry* **86**, 401–410.

O'Hara, K.L., Boncina, A., Diaci, J., Anic, I., Boydak, M., Curovic, M. *et al.* 2018 Culture and silviculture: origins and evolution of silviculture in Southeast Europe. *Int. For. Rev.* **20**, 130–143.

Otto, H. 2000 Silvicultural experiences after catastrophic hurricanes: insights from the past in lower Saxony. *Rev. For. Fr.* **52**, 223–238.

Palik, B.J., D'Amato, A.W., Franklin, J.F. and Johnson, K.N. 2021 *Ecological Silviculture: Foundations and Applications*. Waveland Press, p. 343.

Peura, M., Burgas, D., Eyvindson, K., Repo, A. and Monkkonen, M. 2018 Continuous cover forestry is a cost-efficient toll to increase multifunctionality of boreal production forests in Fennoscandia. *Biol. Conserv.* **217**, 104–112.

Pommerening, A. and Murphy, S.T. 2004 A review of the history, definitions and methods of continuous cover forestry with special attention to afforestation and restocking. *Forestry* **77**, 27–44.

ProSilva 2012 *ProSilva Principles*, p. 67. https://www.prosilva.org/close-to-nature-forestry/pro-silva-principles/ (accessed on 10 June 2021).

Puettmann, K.J., Wilson, S.M.G., Baker, S.C., Donoso, P.J., Drossler, L., Amente, G. *et al.* 2015 Silvicultural alternatives to conventional even-aged forest management – what limits global adoption? *For. Ecosyst.* **2**, 8.

Purser, P., Ó'Tuama, P., Vítková, L. and Ní Dhubháin, A. 2015 Factors affecting the economic assessment of continuous cover forestry compared with rotation based management. *Irish For.* **72**, 150–165.

Quine, C.P., Humphrey, J.W. and Ferris, R. 1999 Should the wind disturbance patterns observed in natural forests be mimicked in planted forests in the British uplands? *Forestry* **72**, 337–358.

Ramirez, J.I., Jansen, P.A. and Poorter, L. 2018 Effects of wild ungulates on the regeneration, structure and functioning of temperate forests: a semi-quantitative review. *For. Ecol. Manage.* **424**, 406–419.

Reimoser, F., Armstrong, H. and Suchant, R. 1999 Measuring forest damage of ungulates: what should be considered. *For. Ecol. Manage.* **120**, 47–58.

Roessiger, J., Griess, V. and Knoke, T. 2011 May risk aversion lead to near-natural forestry? A simulation study. *Forestry* **84**, 527–537.

Schall, P. and Ammer, C. 2013 How to quantify forest management intensity in Central European forests. *Eur. J. For. Res.* **132**, 379–396.

Schelhaas, M.J., A.P.P.M. Clerkx, W.P. Daamen, J.F. Oldenburger, G. Velema, P. Schnitger, H. Schoonderwoerd and H. Kramer, 2014. *Sixth Netherlands Forest Inventory: Methods and basic results*. Wageningen, Alterra Wageningen UR (University and Research centre), Alterra-rapport 2545. [in Dutch]

Schelhaas, M.-J., Nabuurs, G.-J., Hengeveld, G., Reyer, C., Hanewinkel, M., Zimmermann, N.E. *et al.* 2015 Alternative forest management strategies to account for climate change-induced productivity and species suitability changes in Europe. *Reg. Environ. Change* **15**, 1581–1594.

Schelhaas, M.-J., Fridman, J., Hengeveld, G.M., Henttonen, H.M., Lehtonen, A., Kies, U. *et al.* 2018 Actual European forest management by region, tree species and owner based on 714,000 re-measured trees in national forest inventories. *PLoS ONE* **13**, e0207151.

Schütz, J.-P. 2001 Opportunities and strategies of transforming regular forests to irregular forests. *For. Ecol. Manage.* **151**, 87–94.

Schütz, J.-P., Pukkala, T., Donoso, P.J. and von Gadow, K. 2012 Historical emergence and current application of CCF. In *Continuous Cover Forestry*. T., Pukkala, K., von Gadow (eds.). Springer Science, pp. 1–28.

Schütz, J.-P., Saniga, M., Diaci, J. and Vrska, T. 2016 Comparing close-to-nature silviculture with processes in pristine forests: lessons from Central Europe. *Ann. For. Sci.* **73**, 911–921.

Tahvonen, O. and Rämö, J. 2016 Optimality of continuous cover vs. clear-cut regimes in managing forest resources. *Can. J. For. Res.* **46**, 891–901.

Tremblay, J.-P., Huot, J. and Potvin, F. 2006 Density-related effects of deer browsing on the regeneration dynamics of boreal forests. *J. Appl. Ecol.* **44**, 552–562.

UNECE. 2014 *The Value of Forests: Payments for Ecosystem Services in a Green Economy. Geneva Timber and Forest Study Paper 34*. United Nations. https://www.unece.org/fileadmin/DAM/timber/publications/SP-34Xsmall.pdf (accessed on 2 June 2020).

Valkonen, S. and Cheng, Z. 2014 Attitude of professional foresters to continuous-cover forestry. *Metsätieteen aikakauskirja* **2014**, 114–118 (in Finnish).

Vítková, L., Ní Dhubháin, Á., Tuama, O.P. and Purser, P. 2013 The practice of continuous cover forestry in Ireland. *Irish For.* **70**, 141–156.

Wilson, S.M.G. 2013 Adoption of alternative silvicultural systems in Great Britain: a review. *Q. J. For.* **107**, 279–293.