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

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Received 19 March 2021

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 Futaié 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...
use of ‘nature-based management’ were based on conventional appreciably. is that they recognize that CCF differs substantially from RFM, (Duncker planting, more intensive site management, shorter rotations and Combined objective forestry differs from CCF in greater use of has to be modified to take account of multifunctional objectives. FMA on 18 per cent of European forests, second ranked after (Duncker (lowest intensity) to ‘short rotation forestry’ (highest intensity) these FMAs ranged from ‘unmanaged forest nature reserve’ (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 CF 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 Angestam, 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
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.prosila.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 (Bonacci, 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
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.

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

<table>
<thead>
<tr>
<th>Country</th>
<th>RFM – silvicultural systems</th>
<th>CCF – silvicultural systems</th>
<th>Notes (with source year for data if known)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clear-felling</td>
<td>Uniform shelterwood</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strip shelterwood</td>
<td>Seed tree</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>Single stem selection</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Group selection</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Irregular shelterwood</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Undergoing transformation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>to CCF</td>
<td></td>
</tr>
<tr>
<td>Albania</td>
<td>100</td>
<td>45</td>
<td>Data derived from NFI (2004)</td>
</tr>
<tr>
<td>Austria</td>
<td>ND</td>
<td>ND</td>
<td>Estimate (G. Ligot and C. Sanchez, personal communication)</td>
</tr>
<tr>
<td>Belgium</td>
<td>55</td>
<td>45</td>
<td>Z. Govedar, personal communication</td>
</tr>
<tr>
<td>Bosnia and Hersegovina</td>
<td>90</td>
<td>90</td>
<td>General Forest Management Plan (2016)</td>
</tr>
<tr>
<td>Croatia</td>
<td>4</td>
<td>48</td>
<td>NFI data supplemented by national questionnaire (2017)</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>75</td>
<td>18</td>
<td>Estimate based on NFI data (2017)</td>
</tr>
<tr>
<td>Denmark</td>
<td>76</td>
<td>7</td>
<td>Based on fellings recorded in Yearbook Forest 2017. No distinction between different shelterwood systems</td>
</tr>
<tr>
<td>Estonia</td>
<td>90</td>
<td>9</td>
<td>Based on official statistics for fellings (2017)</td>
</tr>
<tr>
<td>Finland</td>
<td>80</td>
<td>17</td>
<td>Estimate (ProSilva France 2019)</td>
</tr>
<tr>
<td>France</td>
<td>75</td>
<td>25</td>
<td>Estimate (P. Spahel, personal communication)</td>
</tr>
<tr>
<td>Germany</td>
<td>20</td>
<td>40</td>
<td>Estimate (Continuous Cover Forestry Group 2019)</td>
</tr>
<tr>
<td>Great Britain</td>
<td>84</td>
<td>1</td>
<td>Derived from NFI (1992)</td>
</tr>
<tr>
<td>Greece</td>
<td>6</td>
<td>1</td>
<td>Derived from official data (2019)</td>
</tr>
<tr>
<td>Hungary</td>
<td>64</td>
<td>29</td>
<td>Based on 2012 data for the Republic of Ireland (Vítková et al., 2013)</td>
</tr>
<tr>
<td>Ireland</td>
<td>98</td>
<td>&lt;1</td>
<td>Derived from NFI (2005). No distinction between single stem and group selection</td>
</tr>
<tr>
<td>Italy</td>
<td>43</td>
<td>37</td>
<td>Based on official information on final fellings and on chace of management regime (2018)</td>
</tr>
<tr>
<td>Kosovo</td>
<td>ND</td>
<td>1</td>
<td>Based on official information on final fellings in state forests (2016)</td>
</tr>
<tr>
<td>Latvia</td>
<td>92</td>
<td>1</td>
<td>Z. Govedar, personal communication</td>
</tr>
<tr>
<td>Lithuania</td>
<td>95</td>
<td>4</td>
<td>Derived from NFI report of Schelhaas et al. (2014)</td>
</tr>
<tr>
<td>Montenegro</td>
<td>&lt;1</td>
<td>84</td>
<td>Information from national forests enterprise (2018)</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>56</td>
<td>13</td>
<td>Other is the ‘mountain selection system’. Derived from 2013 data: <a href="https://www.nibio.no/tema/skog/skogbehandling-og-skogskjotsel/foryngelseshogst">https://www.nibio.no/tema/skog/skogbehandling-og-skogskjotsel/foryngelseshogst</a></td>
</tr>
<tr>
<td>North Macedonia</td>
<td>64</td>
<td>9</td>
<td>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 NFI (2010)</td>
</tr>
<tr>
<td>Norway</td>
<td>74</td>
<td>18</td>
<td>Derived from Statistical Yearbook of Romania, 2017. Other is group shelterwood</td>
</tr>
<tr>
<td>Poland</td>
<td>64</td>
<td>30</td>
<td>Diao et al., 2012</td>
</tr>
<tr>
<td>Portugal</td>
<td>79</td>
<td>18</td>
<td>Estimate – M. Saniga and R. Bručnik, personal communication</td>
</tr>
<tr>
<td>Romania</td>
<td>3</td>
<td>2</td>
<td>Yearly report of Forest Service (2018)</td>
</tr>
<tr>
<td>Serbia</td>
<td>91</td>
<td>&lt;1</td>
<td>Estimate since no official data – G. Miaillier, personal communication</td>
</tr>
<tr>
<td>Slovakia</td>
<td>16</td>
<td>76</td>
<td>Based on Swedish Forest Agency data on final fellings (2017)</td>
</tr>
<tr>
<td>Slovenia</td>
<td>&lt;1</td>
<td>1</td>
<td>Estimate (P. Breng, personal communication)</td>
</tr>
<tr>
<td>Spain</td>
<td>85</td>
<td>5</td>
<td>V. Lavnyy, personal communication</td>
</tr>
<tr>
<td>Sweden</td>
<td>89</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Switzerland</td>
<td>13</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Ukraine</td>
<td>80</td>
<td>17</td>
<td></td>
</tr>
</tbody>
</table>

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.
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 summary of 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).

<table>
<thead>
<tr>
<th>Knowledge gaps</th>
<th>Obstacles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Per cent of total</td>
</tr>
<tr>
<td>1. Applying CCF in an era of climate change (e.g. selecting climate adapted species; managing carbon stores)</td>
<td>31</td>
</tr>
<tr>
<td>2. Resistance and resilience of CCF stands compared with even-aged ones</td>
<td>15</td>
</tr>
<tr>
<td>3. Using mechanized harvesting systems in CCF</td>
<td>14</td>
</tr>
<tr>
<td>4. Limited professional awareness of CCF including lack of examples</td>
<td>14</td>
</tr>
<tr>
<td>5. Poor data on the economic aspects of CCF including timber quality and yields</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 southeastern 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: Nordfjell 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 utilization 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 Ir régulière (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 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 handling 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 CFM 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.

**Acknowledgements**

This paper originated from an invited presentation made at the meeting on ‘Forests for the future - from science to the people’ held in Radlje ob Dravi, Slovenia in September 2019 to celebrate the 30th anniversary of the founding of ProSilva. We are grateful to all the members of ProSilva and other colleagues who answered our questionnaire. Apart from the authors, the following people kindly provided replies outlining the situation in the following countries: Kjell Andreassen (Norway); Igor Anič (Croatia); Valda Araminiene (Lithuania); Orhan Berisha (Kosovo); Peter Brang and Anne Huerzeler (Switzerland); Peter Csépányi (Hungary); Janis Donis (Latvia); Zoran Govedar (Bosnia and Herzegovina, Montenegro); Nikolaos Grigoriadis (Greece); Ulrik Kragh Hansen and Palle Madsen (Denmark); Vasyl Lavravy (Ukraine); Mehmet Metaj (Albania); Marek Myslaić (Estonia); Grégori Miallier (Spain); Frits Mohren (the Netherlands); Noro Niculescu (Romania); Urban Nilsson (Sweden); Maciej Pach (Poland); Paddy Purser (Ireland); Christine Sanchez and Gauthier Ligot (Belgium); Milan Slape and Rudolf Bruchanil (Slovakia); Eckart Senitzka and Georg Frank (Austria); Peter Spathelf (Germany); Massimo Stroppa and Mauro Frattegiani (Italy); Evrard de Turckheim (France); Nikolcho Velkovski (North Macedonia); Tomáš Vrška and Milan Hron (Czech Republic). We are grateful to two referees and Dr Gary Kerr for their helpful reviews of a previous draft of this paper.

**Conflict of interest statement**

None declared.

**Funding**

JC would like to thank FCT - National Foundation for Science and Technology, for support under the Project Scapepfe PCIF/MOS/0046/2017. The other authors did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

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