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Suitability of close-to-nature silviculture for adapting temperate European forests to climate change

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In many parts of Europe, close-to-nature silviculture (CNS) has been widely advocated as being the best approach for managing forests to cope with future climate change. In this review, we identify and evaluate six principles for enhancing the adaptive capacity of European temperate forests in a changing climate: (1) increase tree species richness, (2) increase structural diversity, (3) maintain and increase genetic variation within tree species, (4) increase resistance of individual trees to biotic and abiotic stress, (5) replace high-risk stands and (6) keep average growing stocks low. We use these principles to examine how three CNS systems (single-tree selection, group selection and shelterwood) serve adaptation strategies. Many attributes of CNS can increase the adaptive capacity of European temperate forests to a changing climate. CNS promotes structural diversity and tree resistance to stressors, and growing stocks can be kept at low levels. However, some deficiencies exist in relation to the adaptation principles of increasing tree species richness, maintaining and increasing genetic variation, and replacing high-risk stands. To address these shortcomings, CNS should make increased use of a range of regeneration methods, in order to promote light-demanding tree species, non-native species and non-local provenances.

Introduction

Forest managers face the challenge of integrating a long-term perspective into their decision-making, because forest production cycles cover long periods, often exceeding 100 years. While meeting changing societal demands was always a challenge, site conditions – especially climate parameters – have generally been assumed to be more or less constant. This assumption is no longer valid as the climate is changing, which in turn affects site

factors such as air temperature, water availability (IPCC, 2013), storm patterns (Blennow and Olofsson, 2008; Donat *et al.*, 2010) and fire risks (McCoy and Burn, 2005; Moriondo *et al.*, 2006). Global and regional projections for the direction of change in these site factors exist, but the speed of change remains uncertain as does the magnitude and frequency of extreme events (IPCC, 2013).

There is increasing evidence that climate change is already affecting tree growth and tree mortality (van Mantgem *et al.*,

2009; Allen *et al.*, 2010). Higher temperatures shorten development cycles of disease and pest organisms (Hlásny and Turcáni, 2009; Jönsson *et al.*, 2011) and have been shown to favour their latitudinal and altitudinal expansion (Battisti *et al.*, 2005). There is also mounting evidence of a direct link between climate-induced greater occurrence of forest diseases and pests and increased tree mortality (Sturrock *et al.*, 2011).

In forest management, the magnitude of the projected climatic changes – with best estimates of temperature increases between 1.1 and 4.8°C by the end of the twenty-first century in comparison to the reference period 1986–2005 in three out of four scenarios (IPCC, 2013) – and the associated uncertainty create the need for a re-evaluation of silvicultural practices. Historically, these have been developed to meet societal needs in a specific economic, societal and environmental context and in particular forest types. If this context alters – and this is the case if the climate as one principal determinant of the forest environment changes –, it cannot be assumed that these silvicultural practices continue to be appropriate. Specific practices are likely to exhibit particular strengths and weaknesses.

Several recent contributions have addressed the issue of adapting forest management to climate change and future uncertainty (Spittlehouse and Stewart, 2003; Broadmeadow *et al.*, 2005; Millar *et al.*, 2007; Rigling *et al.*, 2008; Innes *et al.*, 2009; Bolte *et al.*, 2009, 2010a; Stokes and Kerr, 2009; Lindner *et al.*, 2010; Seidl *et al.*, 2011; O'Hara and Ramage, 2013; Rist *et al.*, 2013). The arguments of these contributions are generally based at a conceptual level, e.g. in terms of ecological stability (Grimm and Wissel, 1997) or adaptive capacity (Lindner *et al.*, 2010). The term adaptive capacity is here defined as the ability of forest ecosystems either to absorb climatic change without major changes in forest composition and structure (resistance, Grimm and Wissel, 1997), or to rebuild themselves, possibly with a different composition and structure, after disturbances caused or triggered by climatic influences (resilience), or to evolve continuously, and not abruptly, in composition and structure. Increased adaptive capacity would ensure that forests continue to deliver a broad range of ecosystem services (O'Hara and Ramage, 2013).

These contributions have not satisfied the demand for guidance on how specific silvicultural practices should be changed in response to a changing climate. Only few papers have attempted to address climate change adaptation in forestry at a more specific and local level (Brang *et al.*, 2008; Kohnle *et al.*, 2008; Kohler *et al.*, 2010; Puettmann, 2011). To satisfy the need for immediate guidance, forest administrations and large forest enterprises in several European countries have published preliminary operational guidelines to advise forest managers on how to modify silvicultural practice in response to climate change, e.g. by promoting particular tree species and reducing the use of others (e.g. Bayerische Staatsforsten, 2008; Kantonsforstamt St. Gallen, 2008; Forestry Commission Wales, 2010).

This review paper aims to provide a more scientific basis for such guidelines. Specifically, we will (1) examine the principles proposed for climate-adapted forest management, (2) demonstrate the implementation of these principles in silvicultural practices and (3) examine to what degree these principles and practices are already applied in a specific type of silviculture, i.e. close-to-nature silviculture (CNS).

The procedure used to examine how well a silvicultural system meets the crucial requirements of adaptation to climate change

can be applied to any silvicultural system and to forests in any region of the world. Here we decided to apply it to CNS since an influential body of forest managers in Europe view CNS as particularly suitable for managing forests in a changing climate (Reif *et al.*, 2010). This approach is increasingly widely applied in Central Europe, where there is a very long tradition of its use, and partly also in Southern Europe, where CNS approaches have also been applied locally. This geographical range of application is the reason why our review focuses on forests of the temperate zone of Europe, including mountain forests of Southern Europe.

Our decision to examine how well CNS adopts principles of climate change adaptation should not be taken as an uncritical endorsement of CNS. It is also not our aim to investigate how far CNS emulates natural processes, but instead to examine CNS as practised on the ground and described in the literature.

Principles and practices for climate change adaptation in forest management

This section focuses on silvicultural adaptation strategies, their rationale and their implementation. To differentiate between the strategic and the operational level of adaptation in forest management, strategic elements are called 'principles', and silvicultural interventions which can be used to operationally implement the principles are termed 'practices'. For instance, the creation of canopy openings of a range of sizes to support regeneration of different species is a practice for implementing the principle 'increase tree species richness'.

The principles and practices considered (Table 1) were compiled from the literature cited in this paper, in particular Spittlehouse and Stewart (2003); Broadmeadow *et al.* (2005); Millar *et al.* (2007); Brang *et al.* (2008); Rigling *et al.* (2008); Innes *et al.* (2009); Stokes and Kerr (2009); Bolte *et al.* (2010a); Lindner *et al.* (2010) and Seidl *et al.* (2011). Our list does not include the general principle of site-adapted silviculture, since this is a basic tenet of European forest management including CNS (Wiebecke, 1990), and covers site-specific tree species selection and variations in management intensity, target stand structures and production cycles. It also implies that site-specific management constraints are respected to maintain the production potential of a site by, e.g. limiting the impact of heavy harvesting machinery on soils and the remaining stand to acceptable levels (Edeso *et al.*, 1999).

The following section describes how each adaptation principle enhances the adaptive capacity of forests in response to a changing climate, and outlines those silvicultural practices which can be used to implement a given principle.

Increase tree species richness

This principle calls for maintaining or increasing tree species richness at the stand scale. Tree species richness is integrally linked with adaptive capacity because mixed stands are slightly more resistant to disturbance events such as drought or storms (von Lüpke and Spellmann, 1999; Schütz *et al.*, 2006; Knoke *et al.*, 2008; Lebourgeois *et al.*, 2013), and more resilient once a disturbance has occurred (Brang, 2001; Jactel *et al.*, 2009). In mixed stands, tree species may occupy different niches. While there is strong evidence for complementary use of light (Pretzsch and Schütze, 2005), results are contradictory for complementary use

Table 1 Relationship between climate change adaptation principles and silvicultural practices

Practices	Principles					
	1. Increase tree species richness	2. Increase structural diversity	3. Maintain and increase genetic variation within tree species	4. Increase resistance of individual trees to biotic and abiotic stress	5. Replace high-risk stands	6. Keep growing stocks low
Single-tree selection cutting (incl. transformation cuts)		X		X		
Regeneration cuts	X	X	X			X
Long regeneration periods		X	X			
Maintenance of seed trees	X	X	X			
Natural regeneration	X	X	X			
Artificial regeneration	X			(X)		
Introducing provenances of the same species			X	(X)		
Tending	X					
Thinning	(X)	X		X		X
Reducing impact of felling operations				(X)		
Reduced rotation length				X	X	X
Control of ungulates	X	X		(X)		

X means a practice can be used to fully implement a principle, (X) means a practice may partially contribute to implementing a principle.

of the rooting zone (Meinen *et al.*, 2009; Krämer and Hölscher, 2010; Pretzsch *et al.*, 2013). As the interactions between species that may lead to complementarity are highly dynamic in space and time and also depend on stand density (Forrester, 2014), it is not surprising that contradictory results may occur even for the same species mixture. However, species often have different tolerance to climatic factors so that mixtures provide a hedge against uncertain future conditions. The ecological insurance concept postulates that more diverse communities are more likely to cope with new conditions when subject to unpredictable stress or disturbance (Yachi and Loreau, 1999). With an increasing number of functionally different species, the probability increases that some of these species can resist external disturbances or changing environmental conditions. In addition, the probability increases that one species can take over the role of another, redundant species that does not survive the disturbance or new conditions (Walker *et al.*, 1999; Yachi and Loreau, 1999). For example, most biotic disturbance agents are highly species-specific. Examples are the bark beetle *Ips typographus*, which attacks Norway spruce (*Picea abies*), but not broad-leaved species or silver fir (*Abies alba*) (Wermelinger, 2004), the bark beetle *Matsucoccus feytaudi*, which is less aggressive in mixed than in pure maritime pine (*Pinus pinaster*) stands (Jactel *et al.*, 2006), and the ash dieback (*Hymenoscyphus pseudoalbidus*), which affects *Fraxinus excelsior* (Kjær *et al.*, 2012). An additional point is that mixed stands increase future management options and future possibilities for natural regeneration.

However, more species-rich stands may not always be better in all aspects relevant to adaptation to climate change. An often overlooked issue is that of water use in mixtures. Several studies have found higher water use of the tree layer in mixture when compared with monocultures of the same species (Schume *et al.*, 2004;

Anders *et al.*, 2006; Forrester *et al.*, 2010). These findings demonstrate potential trade-offs between promoting tree species diversity and other functions which may increase in importance in future such as the provision of water or the susceptibility to drought stress.

One of the most important practices used to increase species richness is the choice of regeneration cut. The natural establishment of several species can be supported by creating large variations in light conditions, allowing both light-demanding and shade-tolerant species to regenerate (e.g. group selection in combination with strip cuts). In young growth originating from natural regeneration, enrichment planting is a valuable practice to introduce additional species. Once young trees are established, species richness should be maintained by appropriate tending measures. In subsequent development stages, thinning is important to maintain rare species or species with low competitiveness, in particular if they are adapted to a warmer and drier climate (Brang *et al.*, 2008). Finally, the successful establishment of species-rich stands depends very much on the control of ungulates (Gill, 1992; Götmark *et al.*, 2005). In order to achieve the optimal adaptive effect of species mixtures, large mono-specific patches should be avoided and the pattern of the mixture designed so that it is robust (i.e. one species does not quickly outgrow others) and can be easily and effectively managed. Very intimate mixtures usually require high tending investments and should therefore be avoided.

Increase structural diversity

The presence of trees of different ages and sizes in a forest creates structural diversity, which may be distributed either vertically (e.g. in the single-tree selection system) or horizontally (in patch cut systems). As biotic and abiotic disturbance agents often

specifically affect trees of a specific size range, it seems a safe assumption – by analogy with the above-mentioned insurance hypothesis – that structurally diverse forests will exhibit a higher overall resistance. For instance, many studies report increased susceptibility to wind damage with tree height (e.g. König, 1995; Mayer *et al.*, 2005; Mitchell, 2013). But small trees are not only blown over less often by storms than large ones, but may also be less attractive to bark beetles. In contrast, large trees may be less susceptible to frost, drought and fire than small trees. The resilience of vertically structured stands after wind and insect disturbance is large because the advance regeneration present will be quickly released (Frehner *et al.*, 2005). Increasing structural diversity makes it unlikely that disturbances affect all trees in a forest (Bolte *et al.*, 2010b; O'Hara and Ramage, 2013). It leaves legacies and thus makes forests more resilient (Franklin *et al.*, 2000; Gustafsson *et al.*, 2010; O'Hara and Ramage, 2013). Higher resistance and resilience mean higher adaptive capacity. An exception may be forests in areas with high fire risk, where vertical continuity of fuel between canopy layers provides a 'ladder' which makes it easier for fires to reach the upper canopy. Therefore, this structure may be associated with fires of higher intensity and faster horizontal propagation (Gonzalez *et al.*, 2006), causing much more destruction.

Structural diversity can be mainly achieved using uneven-aged silvicultural systems (single-tree selection), systems with long regeneration periods (e.g. group selection systems) and transformation cuts (Schütz, 2001) leading to irregular stand structures and uneven-aged stands. To a lesser extent, crown thinning can also increase structural diversity if used to create two-layered stands. Regeneration cuts can be combined with underplanting or direct seeding of a desired admixed tree species that will increase tree species richness. Mixing tree species of different shade-tolerance which grow to different sizes clearly supports the aim of maintaining or creating structurally diverse stands. In addition to increasing the variation in tree size classes at the stand level, structural diversity, which encompasses more than variation in tree dimensions (McElhinny *et al.*, 2005), may be increased through a variety of other measures such as specific retention of structural elements aimed to maintain ecosystem functioning (Gustafsson *et al.*, 2012).

Maintain and increase genetic variation within tree species

The adaptive capacity of forest tree populations to climate change also depends on genetic variation. One expression of genetic variation is local adaptation, which has been shown in numerous provenance trials and common garden experiments, although the underlying mechanisms are only partly understood (Aitken *et al.*, 2008).

Therefore a first approach to ensuring adaptive capacity is to maintain existing genetic variation in tree populations. Natural regeneration and long regeneration periods (for shade-tolerant species only) are well suited to regenerate stands with a high seedling density from many parent trees (Finkeldey and Ziehe, 2004), to ensure high genetic variation. However, natural regeneration also conserves the genetic material that may originate from poorly adapted planted trees or from populations with low genetic variation. Tending and thinning operations usually favour individual trees with traits which are relevant for timber production, e.g. stem straightness. However, the process of selecting these

desirable individuals may reduce variation important for adaptive capacity in the wider population (Finkeldey and Ziehe, 2004; Paffetti *et al.*, 2012).

A second approach to increase genetic variability consists of enriching existing populations with other provenances, especially for species with a small within-population variation, but high variation between seed sources. The approach includes multiple population breeding (Eriksson *et al.*, 1993; Eriksson, 2001). A third possibility to maintain or enhance genetic variation is to exert variable selective pressure on trees by practicing diverse cutting regimes, which provide different ecological niches with respect to, e.g. light exposure and soil humidity. Variable selective pressure can also result from long regeneration periods where inter-annual climatic variation produces fluctuating environmental conditions.

The main silvicultural practices to achieve high genetic variation are long-term natural regeneration processes (applicable to shade-tolerant species) and enrichment planting, in particular if provenances from warmer and drier climates are used (Aitken *et al.*, 2008; Finkeldey, 2010). Enrichment planting will depend upon an adequate supply of seed and seedlings of suitable provenances being available from seed stands, seed orchards and nurseries.

Increase resistance of individual trees to biotic and abiotic stress

Individual trees can exhibit different stress resistance. For instance, many studies have found a higher resistance to snow break in sturdier trees, i.e. those with a small coefficient of slenderness (height (m) dbh⁻¹ (cm), Rottmann, 1985) and long crowns. Norway spruce trees with higher vitality (e.g. expressed by higher live crown ratios) recovered more easily from heavy SO₂ pollution (Šlodičák, 1988). Moreover, vigorous trees, e.g. dominant or co-dominant crown classes, are more resistant to biotic pests, especially at low and medium infestation densities (Wenk and Apel, 2007). However, early reduction of tree density to improve individual tree vigour (Cameron, 2002) may reduce genetic diversity (Finkeldey and Ziehe, 2004).

Heavy thinning, which provides individual trees with more growing space and thus with more soil volume for their root system, may also improve the resistance and resilience of trees to drought stress (Kohler *et al.*, 2010). It appears that providing trees with more growing space promoted recovery after drought more than actual resistance to drought (Sohn *et al.*, 2012, 2013). However, whether increased growing space is also advantageous under extreme drought conditions has so far not been sufficiently investigated.

The main silvicultural practice to develop long-crowned trees is the consistent use of thinning from above, and in particular heavy interventions at the pole stage. In hardwood trees, this is commonly commenced as soon as self-pruning has eliminated branches on the lower 6–10 m of the bole. Such thinning regimes usually lead to large trees with high live crown ratios (Spiecker *et al.*, 2009).

Replace high-risk stands

Stands can be at high risk of being damaged by disturbances such as storms, forest fires or insects. Examples are stands consisting of species and/or provenances which are poorly adapted to the site already under current climate, stands with short-crowned and

slender trees, with low individual and collective resistance to wind and snow break, stands already destabilized by felling or previous disturbance, which have abruptly exposed stems to sun scorch, or stands with high fuel loads. Such stands are at high risk from further natural disturbance, which may not only reduce income from timber sales, but also endanger ecosystem services such as the protective function against gravitational hazards on steep slopes. Salvage harvesting after disturbance usually incurs economic losses because the timber may be damaged, the harvesting operations may be more expensive than in planned fellings, or the timber prices may be low due to over-supply. Climate change can increase these risks since tree vigour may be reduced (e.g. due to drought, Bréda *et al.*, 2006), and disturbances may be more frequent (e.g. by bark beetles). Such risks, and associated economic losses, can be reduced if high-risk stands are replaced prematurely with less vulnerable stands (Staupendahl and Möhring 2011) using appropriate silvicultural systems such as modified clear-cutting or group and strip-felling, or transformation to uneven-aged stands (von Lüpke *et al.*, 2004).

Keep average growing stocks low

One rationale for maintaining relatively low growing stocks in forests lies in smaller economic risks because the amount of financial loss caused by any disturbance depends on growing stock, i.e. the capital at risk (Usbeck *et al.*, 2010). This would be true even if the pressure (e.g. speed of wind gusts) and the damage of a disturbance event to a stand were independent of its growing stock. However, high growing stocks are correlated with increased damage susceptibility. In the case of storms, a greater stand age and a taller stand height increase stand susceptibility (Spiecker, 2003; Mayer *et al.*, 2005). In the case of forest fires, a high growing stock connected to high stand densities in Mediterranean forests can also lead to higher canopy fuel loads (e.g. Mitsopoulos and Dimitrakopoulos, 2007), which, together with biomass connectivity at the landscape scale, can contribute to an increased risk of large fires (Loepfe *et al.*, 2010; Nocentini and Coll, 2013). Another rationale for low growing stocks is that, in particular in southern Europe, increasingly limited water resources will not sustain current growing stocks. Reduced growing stocks can be implemented by earlier final harvests or heavier thinnings (see principle 4). Target growing stocks will vary widely between sites and regions, and be higher on productive sites and when risks are small.

It should be noted that growing stock is directly related to carbon storage. A lower growing stock implies less carbon storage in the forest than with higher growing stocks. This implies that implementing low growing stocks may impose limits to mitigation capacity.

Relative importance of the six adaptation principles

It is not possible to rank the relative importance of the six principles since the ranking depends on the management goals of individual forest owners, the condition of the particular stands in question, the site conditions and the disturbance regime. For example, in a near-natural, mature European beech (*Fagus sylvatica*) stand, tree species richness and structural diversity are probably more relevant than an increase of the individual tree resistance (which is barely achievable at this late development stage) or a reduction of the growing stock. In contrast, in a thicket of poorly adapted

Norway spruce, promoting tree species richness, if not too late, and increasing the individual tree resistance are important issues.

Before we examine how far CNS is compatible with the six principles, we will outline how CNS developed in Europe, and establish a classification of CNS into types since different variants of CNS have developed in response to social, environmental and economic factors.

History and classification of CNS types in Europe

CNS originated in central Europe, where different silvicultural systems were applied in small farm or community mountain forests under the designation 'Plenterwald' (plenter forest, Schütz, 1994) or 'jardinage'. CNS was first described in the nineteenth century and has been widely practised since then in some regions of Europe. Since 1980, CNS has developed from a specialist application to a mainstream approach in several central European countries. This approach is also widely known as Continuous Cover Forestry (Pommerening and Murphy, 2004).

One of the earliest scientific promoters of CNS was Gayer who worked in southern Germany and observed significant damage caused by various disturbances in planted even-aged forests dominated by Norway spruce. As an alternative, he advocated mixed forests with heterogeneous structures in the belief that they would be less prone to disturbance (Gayer, 1886). In France, Gurnaud (1886) advocated the traditional selection system ('jardinage') as an alternative to shelterwood cuttings in irregular mountain forests, and proposed a simple but highly effective monitoring and planning method for irregular forests ('méthode du contrôle'). This method was later modified (Schaeffer *et al.*, 1930; Leclerc *et al.*, 1998). In parallel to the 'jardinage' system, the 'method of natural regeneration with thinnings' proposed by Hartig (1808) was promoted by the national forestry school of Nancy in its silviculture course (Lorentz and Parade, 1837), with a method of natural regeneration 'with successive cuttings' notably for beech and oak (*Quercus spp.*) forests.

In Slovenia, Hufnagl (1893) promoted selection forest management in mountainous regions at the end of the nineteenth century. This system has been widely applied in Slovenia, Croatia and Bosnia by generations of foresters. There was a parallel development in Switzerland where Biolley (1901) promoted the plenter forest and implemented it in the forests of the canton of Neuchâtel, and where Engler (1900) advocated natural regeneration and mixed forests. Later Leibundgut (1948) refined the 'Femelschlag' (group selection or irregular shelterwood system), and introduced the idea of 'free choice of cuttings'.

In the 1920s, a special form of CNS developed in northern Germany, when Möller (1922), inspired by tropical rainforests, developed the 'continuous forest' ('Dauerwald' in German, Helliwell, 1997) approach to increase forest stability and to maintain forests as intact 'organisms'. The Dauerwald approach influenced many private forest owners and was pursued after the Second World War in the association 'Arbeitsgemeinschaft Naturnahe Waldwirtschaft', which may be translated as 'working group on close-to-nature forestry'. Members of this group and other advocates of CNS established Pro Silva Europe in 1989 (Johann, 2006). In parallel, the Italian silviculturist Pavari (1914, 1948) authored several papers to present his idea of 'selvicoltura naturalistica'

(Ciancio, 2010) based on mixed forests with heterogeneous structures and natural regeneration. The origin of this approach can be traced back to the fifteenth century in the eastern Alps, when the Republic of Venice established rules for selection felling (Volin and Buongiorno, 1996).

After the Second World War, even-aged high forest silvicultural systems with fast-growing conifers were dominant in most of central and northern Europe, and also in some parts of southern Europe. Timber production was the main focus of forest management. At a regional scale, CNS was only retained in Slovenia and Switzerland and in some districts of Austria, Croatia, France and Germany. In Slovenia, CNS continued to be practiced throughout the country in different forms (Mlinšek, 1968; Diaci, 2006). In Italy, Susmel (1956) defined structural models for uneven-aged mixed Alpine stands; his intensive work contributed to spreading the application of ‘selvicoltura naturalistica’ in eastern Alpine regions.

From the 1980s onwards, there was a revival of interest in CNS. The main reasons for this were: (1) Increasing environmental awareness, which found expressions in high-level international conferences such as the United Nations Conference on Human Environment in Stockholm in 1972 and the United Nations Conference on Environment and Development in Rio in 1992 (Kerr, 1999). These conferences were followed by subsequent political processes aiming at sustainable forest management such as the Helsinki process in Europe. (2) Large-scale disturbances such as the 1972 storms in northern Germany, and storms of 1990 and 1999 in central Europe, as well as anecdotal evidence that even-aged plantations had been damaged more than forests managed using CNS (Mason, 2002). (3) The high economic costs associated with the establishment phase of even-aged plantations made a low-input management system with reliance on natural processes (e.g. natural regeneration) an attractive alternative to intensive management.

Currently, CNS is a prevailing forest management paradigm in many European regions. However, the uptake of CNS is not consistent, and its forms vary. For example, Denmark has adopted CNS as the main management system (Larsen and Nielsen, 2007) whereas in the other Scandinavian countries there is widespread resistance to CNS. In Atlantic Europe (Portugal, south-west France, the British Isles) and in Spain, implementation of CNS is of recent origin and arguably was constrained by large plantations, mainly of non-native species (e.g. Malcolm *et al.*, 2001; Mason, 2003; Barcenilla *et al.* 2005). Moreover, CNS is not an approach with a commonly agreed definition (Zingg, 1999; Pommerening and Murphy, 2004; Duncker *et al.*, 2012). It is rather a compilation of several principles which are given different weight in different CNS types. These principles comprise

- (1) Promotion of natural and/or site-adapted tree species, often based on the assumed potential natural vegetation,
- (2) promotion of mixed forests,
- (3) promotion of diverse vertical and horizontal stand structures,
- (4) promotion of natural regeneration,
- (5) silvicultural practices that focus on individual trees,
- (6) avoidance of clear cuts.

In addition, CNS often adopts principles that are common to sustainable forest management, e.g. reduction of harvesting damage to remaining stands and the soil, refraining from the use

of pesticides and mineral fertilizers (Ammer *et al.*, 2011), conservation of valuable habitats and control of ungulate populations to permit natural regeneration without protective measures (Vospernik and Reimoser, 2008).

As CNS practices are very diverse, a general assessment of how appropriate CNS is for increasing the adaptive capacity of European forests in response to a changing climate seems impossible. However, the task can be facilitated by classifying CNS into three contrasting types, based on the size and lifespan of contiguous cutting areas in the regeneration phase. The three types are:

- (1) Single-tree selection, which also includes ‘continuous forest’ (Dauerwald in German, Heyder, 1986)
- (2) Group selection (Matthews, 1994; Puettmann *et al.*, 2009; Larsen *et al.*, 2010)
- (3) Shelterwood (Röhrig *et al.*, 2006)

Our reason for including the shelterwood system in our classification is that it embodies some of the principles of CNS, although to a much lesser extent than the single-tree and group selection systems. For example, a uniform shelterwood with a regularly spaced overstorey and low structural diversity can be taken to indicate the outer boundary of what might be considered as a CNS type. Group and irregular shelterwood systems can be considered as being intermediate between the uniform shelterwood and the two selection systems.

Different CNS types can be combined if managers do not implement a silvicultural system rigidly, but conduct interventions flexibly based on a careful assessment of each stand and adjust the intervention to its current condition (O’Hara, 1998). This is known from Slovenia and Switzerland, and leads to one of the above-mentioned CNS types enriched with elements from others, or even to a ‘free-style’ CNS (Mlinšek, 1968; Boncina, 2011). For instance, overstorey shelter, which is the main characteristic of the shelterwood system, is often also used in group selection, thus leading to irregular shelterwood CNS types.

How far do CNS types comply with the six adaptation principles?

In Table 2 we have used our expert judgment to rate each of these three CNS types against the climate adaptation principles and to determine whether a type meets the principle fully, partially or not at all.

Evaluation of the single-tree selection system

Interestingly, the single-tree selection system is rated second highest in terms of the number of climate change adaptation principles it meets fully, but is also the highest ranked of the three CNS types in terms of principles not met (Table 2). Single-tree selection complies with the principle of increasing structural diversity. Moreover, most overstorey trees have high live crown ratios of >50 per cent (Zingg, 2003) and low height : diameter ratios and are thus relatively resistant to abiotic stress (Mason, 2002). The continuous natural regeneration, which is an intrinsic part of single-tree selection (Schütz, 1997), supports the maintenance of genetic variation within species (Finkeldey and Ziehe, 2004), except for target diameter harvesting (see below). Single-tree selection in

Table 2 Ability of three CNS types to implement six principles of climate change adaptation

CNS type	Adaptation principles						Number of principles +	Number of principles ±	Number of principles –
	1. Increase tree species richness	2. Increase structural diversity	3. Maintain and increase genetic variation within tree species	4. Increase resistance of individual trees to biotic and abiotic stress	5. Replace high-risk stands	6. Keep growing stocks low			
Single-tree selection system	–	+	±	+	–	±	2	2	2
Group selection system	+	+	+	±	+	±	4	2	0
Shelterwood system	±	–	±	±	±	+	1	4	1

+ Means a CNS type is generally adopting the principle ± means it may adopt it in some cases or partly, – means it is unable to implement the principle.

conifer dominated forests is often practised at high growing stock levels (e.g. 400 m³ ha⁻¹ in central European forests) although it can also be implemented at lower levels (e.g. 300 m³ ha⁻¹, Schütz, 1997).

Nevertheless, single-tree selection has a number of limitations. Most importantly, it only creates very small gaps, favouring a limited number of shade-tolerant species and posing problems for the regeneration of light-demanding tree species (Schütz, 1999; Malcolm *et al.*, 2001; von Lüpke, 2004), and thereby reducing potential species richness. The competitive advantage of shade-tolerant species in small gaps is even greater if no tending occurs, so that light competition determines which young trees survive. Large gaps favourable to light-demanding species are only created by stand-replacing disturbances, e.g. by infrequent storms. Enrichment planting is also often not used in single-tree selection, partly since managers traditionally rely on natural regeneration, and partly because protecting planted saplings against browsing ungulates is difficult since young-growth stages are not concentrated in space. Moreover, non-native species with high adaptive capacity such as Douglas fir (*Pseudotsuga menziesii*) are rarely used, even though they can grow in single-tree selection systems (Pommerening and Schütz, 2013). This further limits the possibility of adaptation by increased tree species richness. Target diameter harvesting, as a variant of the single-tree selection system, may decrease genetic variation since the trees with fastest growth, which tend to have a higher heterozygosity, are preferentially harvested. As a result, these trees may have less opportunity to produce offspring than trees harvested at a later stage (Konnert and Spiecker, 1996; Finkeldey and Ziehe, 2004).

Also, single-tree selection does not allow a radical replacement of high-risk stands, since patch cuts, which cause the loss of the highly uneven-aged plenter structure, are generally avoided. However, single-tree selection rarely produces the uniform and short-crowned trees characteristic of high-risk stands.

This evaluation of the single-tree selection system largely applies also to the transformation of even-aged to uneven-aged forests with selective thinning.

Evaluation of the group selection system

The group selection system is rated highest in terms of the number of climate change adaptation principles that are completely met and this CNS type is not associated with any principles that are not met (Table 2). Like single-tree selection, group selection complies with the adaptation principles of increasing high (small-scale) structural diversity. Thinnings conducted in this system increase the resistance of individual trees to biotic and abiotic stress. The small patch cuts that are a feature of this system can be used as a means of replacing high-risk stands. Finally, group selection can, in principle, be practised at different growing stock levels by heavy thinnings and short rotation lengths, although the latter are sometimes avoided (Reif *et al.*, 2010).

The limitations of group selection systems are similar to those of single-tree selection systems, especially the difficulty to retain shade-intolerant species in small gaps (Malcolm *et al.*, 2001; Mason *et al.*, 2004; von Lüpke, 2004), or if extended regeneration periods are used. However, using a range of gap sizes and a more rapid expansion of gaps can create highly variable light environments in space and time and thus facilitate higher tree species richness than in single-tree selection (von Lüpke, 2004). Less competitive tree species may be outcompeted during young-growth stages if stands are kept at high density and no pre-commercial tending or thinning interventions are conducted, similar to the situation in forest reserves (Heiri *et al.*, 2009). Finally, planting is more often used in group than in single-tree selection systems, where it is unusual (Schütz, 1997), which also helps to increase tree species richness.

Evaluation of the shelterwood system

The shelterwood system is ranked lowest in terms of the number of climate change adaptation principles that are fully met but is second to the single-tree selection system in terms of the principles not met (Table 2). The shelterwood system tends to produce even-aged mono- or two-layered stands (Spurr, 1956). Phases

with high structural diversity are thus rather short-lived, apart from the irregular shelterwood system (Raymond *et al.*, 2009). However, the longer the regeneration period used, which may extend to 30 years, the more structurally diverse the subsequent stand can become. Tree species richness can be promoted by varying the degree of overstorey retention and the length of the regeneration periods (Raymond *et al.*, 2009). As in previous systems, pre-commercial thinning can be conducted to maintain admixed species, although such interventions can also be used to reduce species richness to commercially valuable species. Planting is rarely used to increase tree species richness, but can be integrated as enrichment planting after the final cut where natural regeneration has partly failed or established regeneration has been damaged by the harvesting operations. The reliance on natural regeneration and the relatively long regeneration periods support the maintenance of genetic variation (Table 2). Selective thinning is often conducted to increase the individual resistance of trees to biotic and abiotic stress since high resistance of the seed trees is needed when shelterwood cuts start (Hanell and Ottosson-Lofvenius, 1994). The replacement of high-risk stands using the shelterwood system is possible on wind-firm sites. If advance regeneration is not yet established or if natural regeneration fails, this may entail planting. The shelterwood system is compatible with low growing stocks if production cycles are relatively short and thinnings are consistently applied. Among the three CNS types, the structural diversity is smallest in the shelterwood system, in particular in the uniform shelterwood system (Spurr, 1956).

Overall assessment of the three CNS types

The three CNS types described here – single-tree selection, group selection and shelterwood – are compatible to some extent with the six adaptation principles; only the single-tree and shelterwood systems were not in accord with at least one principle. In eight cases, a principle is only partly fulfilled in a CNS type, often meaning that the fulfilment depends on the use of specific silvicultural practices.

In contrast to common views (Reif *et al.*, 2010), no single CNS type can be viewed as an optimal silvicultural response to a changing climate (cf. Bauhus *et al.*, 2013). This is not surprising since CNS was originally not developed for this purpose, but for timber production in different forest types. However, traditional CNS types have already been modified to accommodate new needs. Examples are requirements to retain habitat trees which have been integrated into CNS in some countries and are now even required under forest certification schemes (Programme for the Endorsement of Forest Certification, Forest Stewardship Council; e.g. MLUV, 2004), although with limited long-term effects (Rosenvald and Löhmus, 2008). In each of the three types, there is also variation in planting, tending and thinning practices, which means that there is still considerable potential to develop these systems further to meet the future requirements of adaptation to climate change. In addition, in forest practice there is often no clear boundary between the three different systems so that intermediate combinations are possible (Raymond *et al.*, 2009).

Within the Triad zonation framework of Seymour and Hunter (1999), CNS is part of the moderate approach with multifunctional areas under ecosystem management (see also O'Hara and Ramage, 2013). In the classification of forest management

approaches by Duncker *et al.* (2012), CNS covers 'Close-to-nature forestry', but is also compatible with most of the basic principles described for 'Combined objective forestry'. These differences occur because Duncker *et al.* (2012) used a management intensity gradient to evaluate existing forest management strategies whereas our classification is based on existing silvicultural terms.

The most flexible CNS system is the group selection system because it provides variation in patch sizes ranging mostly between 0.05 and 0.5 ha. This range creates environmental gradients (in particular light gradients) providing suitable conditions for both shade-tolerant and shade-intolerant tree species. While shade-tolerant species will grow well even in gaps smaller than 0.05 ha, shade-intolerant species do not benefit much from gaps larger than ~0.3 ha (Malcolm *et al.*, 2001; Christopher *et al.*, 2005).

Single-tree selection is the most suitable way to increase or maintain small-scale structural diversity. However, it is less suitable for increasing species richness. In contrast, the shelterwood system, and in particular the uniform shelterwood system, has the lowest structural diversity in the long term, but is more suitable for increasing tree species richness in the next forest generation, by facilitating the introduction of new species or provenances with enrichment planting.

The three different CNS systems have been applied for periods of well over 100 years (Schütz, 1994) in European forests. During this time, these silvicultural systems have been adjusted to particular conditions and one of the objectives of this paper is to encourage this to happen in the future. Today, managers practicing CNS tend sometimes to stick to a fixed set of principles, and to value their personal experience more than scientific evidence or practical knowledge gained in other parts of the world (Puettmann *et al.*, 2008). However, the challenge of climate change means that past experience of how to manage a forest should not constrain its future management.

Conclusion: further checks of the match between adaptation principles and silvicultural systems are needed

Global climate change poses significant challenges and opportunities to forest management (Read *et al.*, 2009), and implies a need for adjusting silvicultural practices used by forest managers. It is unwise to address adaptation without taking account of the full range of adaptation principles and practices. This also implies that some general restrictions on forest management, which apply to all silvicultural systems, should be revised. For instance, restrictions aimed at conserving genetic diversity of local populations may prohibit the use of provenances from outside a planting region, although their robustness against environmental stress (e.g. drought) has been demonstrated in provenance trials (Kätzel and Löffler, 2007). This is an obstacle to enrichment planting.

We show that all six adaptation principles are already used in CNS, albeit to a different degree in different CNS types. CNS is therefore well suited to help forest managers cope with future climate change, and management principles such as promoting mixed stands, structural diversity and individual tree resistance should be maintained. However, no single CNS type is an optimal adaptation strategy in all respects. Particular deficiencies exist in complying with the principles 'increase tree species richness', 'maintain

and increase genetic variation' and 'replace high-risk stands'. To address these shortcomings, CNS should employ a larger variation in regeneration methods which helps to increase species richness by integrating light-demanding tree species, non-native species and non-local provenances. This could be achieved by applying different CNS types at the landscape level.

We expect that other silvicultural systems, and also specific local variants of CNS, exhibit specific advantages and limitations for climate change adaptation. We therefore advocate testing all silvicultural systems against the six adaptation principles described here to identify their strengths and weaknesses as tools for adapting forests to the challenges posed by climate change. The results of such an evaluation can be used to develop region- and site-specific silvicultural systems that enhance forest resilience against an uncertain future.

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Conflict of interest statement

None declared.

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