

Is Close-to-Nature Silviculture (CNS) an adequate concept to adapt forests to climate change?

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Abstract

Climate change projections for Europe suggest increases in temperature, changes in precipitation regimes as well as more frequent and severe weather extremes like heat waves, droughts and storms. As these changes may have a large impact on forest ecosystems, forest management should adapt to maintain vital and productive forests in the future.

This review assesses how close-to-nature silviculture (CNS), which is a widespread silvicultural approach in Central Europe, may cope with projected changes in climate. First, a conceptual model of forest vulnerability is outlined, and used to describe climate change exposure, sensitivity and adaptive capacity of forests. Strategies and options for adaptation, and their compliance with the principles of CNS are then discussed.

Modifications in CNS, such as using exotic tree species and provenances or the assisted migration of well adapted tree species from other climates can enhance adaptive capacity of forests. Moreover, the regeneration of stress-tolerant pioneer species can be supported by applying the whole range of silvicultural systems.

Keywords: *climate change, adaptation, close-to-nature silviculture (CNS), tree species richness, genetic variation*

Zusammenfassung

Ist naturnaher Waldbau ein geeignetes Konzept zur Anpassung von Wäldern an den Klimawandel?

Projektionen zum Klimawandel in Europa deuten auf eine Erwärmung, Änderung der Niederschlagsverhältnisse sowie häufigere und intensivere Witterungsextreme wie Hitzewellen, Trockenheit und Stürme hin. Diese Änderungen können einen starken Einfluss auf Waldökosysteme haben und die Waldwirtschaft sollte sich daran anpassen, um vitale und produktive Wälder in der Zukunft zu erhalten.

Dieser Übersichtsartikel behandelt die Frage, wie der naturnahe Waldbau (close-to-nature silviculture – CNS) als weit verbreiteter waldbaulicher Ansatz in Mitteleuropa mit dem notwendigen Anpassungsbedarf der Wälder im Einklang steht. Zunächst wird ein Konzept zur Abschätzung der Vulnerabilität von Wäldern unter Klimawandel vorgestellt. Danach werden die Vulnerabilitäts-Komponenten ‚Belastung‘, ‚Empfindlichkeit‘ und ‚Anpassungsvermögen‘ beschrieben und Strategien sowie Möglichkeiten für die Waldanpassung und ihre Übereinstimmung mit dem naturnahen Waldbau diskutiert.

Modifikationen im naturnahen Waldbau, wie die Verwendung von eingeführten Baumarten und Baumartenherkünften sowie die unterstützte Verbreitung (assisted migration) von nachweislich gut angepassten Bäumen aus anderen Klimaten können die Waldanpassung verbessern, ebenso die Erweiterung des Spektrums der Waldbausysteme zur Förderung von stresstoleranten Pionier-Baumarten.

Schlüsselworte: *Klimawandel, Anpassung, Naturnaher Waldbau, Baumartenvielfalt, Genetische Variation*

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1 Introduction

Climate is an important driver for environmental change. Globally, land and ocean surface temperature increased by 0.85 °C over the period 1880 to 2012 (Pachauri and Mayer, 2014). In Germany, mean surface air temperature increased by 1.2 °C in 2001 to 2010 when compared to pre-industrial conditions (1855 to 1890) (EEA, 2011). This warming trend was accompanied by more frequent and severe weather extremes, like heat waves, droughts and heavy precipitation events (Min et al., 2011; Wigley, 2009). Also for the future, an increase in frequency and severity of extreme weather events is expected for Central Europe (Donat et al., 2011; EEA, 2011; Gastineau and Soden, 2009).

Climate warming may improve growing conditions and prolong growing seasons, thereby positively affecting forest growth. However, this may only happen when water availability is sufficient (Nemani et al., 2003); on sites with water shortage, more frequent heat waves and droughts likely raise risks of disturbance, mortality and forest loss (Allen et al., 2010; Lindner et al., 2014; Bolte et al., 2009). Further, a higher storm risk may increase the susceptibility of forests to biotic disturbances. This may be especially important for extensive Norway spruce forests in large parts of Europe that suffer already today from high losses due to interacting impacts of windthrow, warming, drought and bark-beetle attacks (Hanewinkel et al., 2013; Bolte et al., 2010; Schlyter et al., 2006; Schelhaas et al., 2003). Therefore, and due to the long-term interaction of long-living forests and future climate change dynamics, forest management and silviculture have to adapt to today's changing environmental conditions in order to maintain vital and productive forests in the future (Kolström et al., 2011; Bolte and Degen, 2010).

In this review, it is examined whether Close-to-Nature Silviculture (CNS), which is a common silvicultural approach in Central Europe, is an adequate concept to adapt forests to climate change. First, we describe the practice of current CNS management. Then, we elaborate on the concept of vulnerability, which includes climate change exposure, sensitivity and exposure, and perform a vulnerability analysis to outline strategies and options for adaptation. Finally, we analyse whether the concept of CNS should be adjusted to support forest adaptation to climate change.

2 Close-to-nature silviculture (CNS)

The origin of close-to-nature silviculture in Germany dates back to the time before the 19th century, when irregular, selective logging was conducted. A dramatic increase in wood demand during the industrial revolution, however, led to an intensification of forest management and the introduction of forestry activities according to more agricultural principles, like soil tillage, fertilization and the spatial-temporal classification of forests into cutting sequences. In the early 19th century huge areas which were deforested and degraded since the Middle Ages were restored to forests. Thereby, German mainstream forestry laid its emphasis on even-aged

high forests with a preference for clear-cutting (Thomasius, 1996). However, gradually many of these even-aged pure forests were lost due to an increasing number of pest attacks and abiotic disturbances. Consequently, the first forest scientists started to recognise that pure (even-aged) stands may not be resistant and resilient enough for long-term economically successful forest management. One of the most prominent advocates of mixed forests at the turn to the 20th century was the silviculturist Karl Gayer, who strongly supported the group selection system for stand regeneration (Heyder, 1986; Gayer, 1886). In the 1920s, Alfred Möller promoted the idea of 'Dauerwald' (continuous-cover-forestry), which was a special variant of close-to-nature forestry. He advocated single-tree oriented interventions, natural regeneration, avoidance of clear-cutting and the maintenance of multi-storied mixed stands (Möller, 1922).

Although first practised mainly by private forest owners, close-to-nature silvicultural management emerged among all forest ownership categories in Germany during the last quarter of the 20th century. Thereby, forest owners responded to new environmental developments and challenges (e. g. forest decline), major disturbances (storms) and the increasing scientific evidence that mixed forests may be more resilient and productive than pure forests (e. g. Brang et al., 2014; Knoke et al., 2008; Pretzsch, 2003).

A central principle of CNS is the utilization of natural processes to guide forest ecosystems with the least amount of energy input (costs) as possible. Other prominent elements of CNS are (Pommerening and Murphy, 2004; Johann, 2006; Spathelf, 1997):

- promotion of natural and (or) site-adapted tree species composition (non-native species, if admixed to native species, are to a small extent accepted),
- promotion of mixed and 'structured' forests,
- avoidance of clear cuts, as far as possible,
- promotion of natural regeneration,
- single-tree oriented silvicultural practices,
- integration of forest ecosystem services (e. g. water, recreation) at small spatial scales.

CNS is thus not a silvicultural system or technique in sensu strictu, but a broad approach with different elements which can be adapted to changing natural and socio-economic conditions (Spathelf, 1997). To date, CNS in the described specification is mainly applied in Central Europe. The practical success of CNS in Germany depends on reduced impact of tending and harvesting on the remaining stand and soil (Reduced Impact Logging) and controlled ungulate populations. CNS is an integrative approach of (sustainable) forest management (SFM) and biodiversity conservation on a small scale (see Schütz, 1999, for a discussion here). When classified according to management intensity, tree species and structural heterogeneity, CNS occupies its place between selection and old-growth forests on the one hand, and forests after larger stand replacement events or even plantations on the other hand (Figure 1, adapted after Puettmann et al., 2009). This classification demonstrates the range of regeneration cuts and forest target structures which are feasible within CNS.

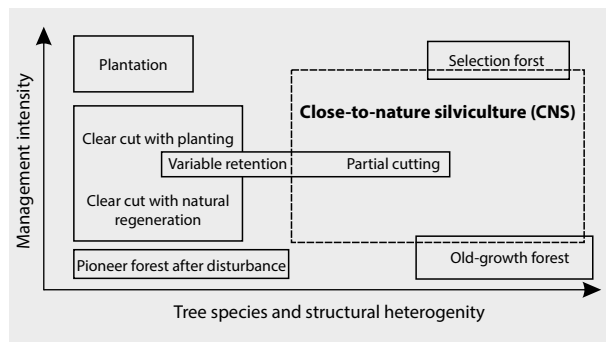


Figure 1

Classification of CNS according to management intensity as well as tree species and structural diversity. Adapted after Puettmann et al. (2009).

3 Climate change vulnerability of German forests

3.1 Definitions and concepts

'Vulnerability' is a widely used term to qualify the impacts of climate change on forest ecosystems. It can be described as the probability with which an environmental system can be damaged through changes in the environment and (or) society, taking into account its adaptive capacity (Turner et al., 2003). In this review, the different elements of vulnerability, being exposure, sensitivity and adaptive capacity (Figure 2), will be defined after Lindner et al. (2010) and IPCC (2007), glossary terms WG II).

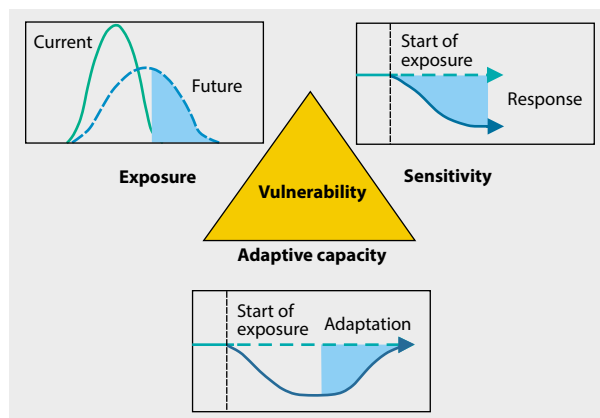


Figure 2

Components of ecosystem vulnerability.

Forest ecosystems are *exposed* to climate factors, such as temperature and precipitation, in different ways (i.e. means, variability and extreme events; Reyer et al., 2013). *Sensitivity* describes the degree to which a system is affected by climate change factors, either adversely or beneficially. *Adaptive capacity*, however, is the ability of a system to adjust to changes in climate, i.e. to prevent or moderate potential damages or to take advantage of opportunities. Finally, vulnerability is

the degree to which a system is susceptible to, and unable to cope with adverse effects of climate change factors, including climate variability and extremes in disturbance events. In the following sections, different elements of vulnerability will be discussed for forests in Germany as an example for Central Europe.

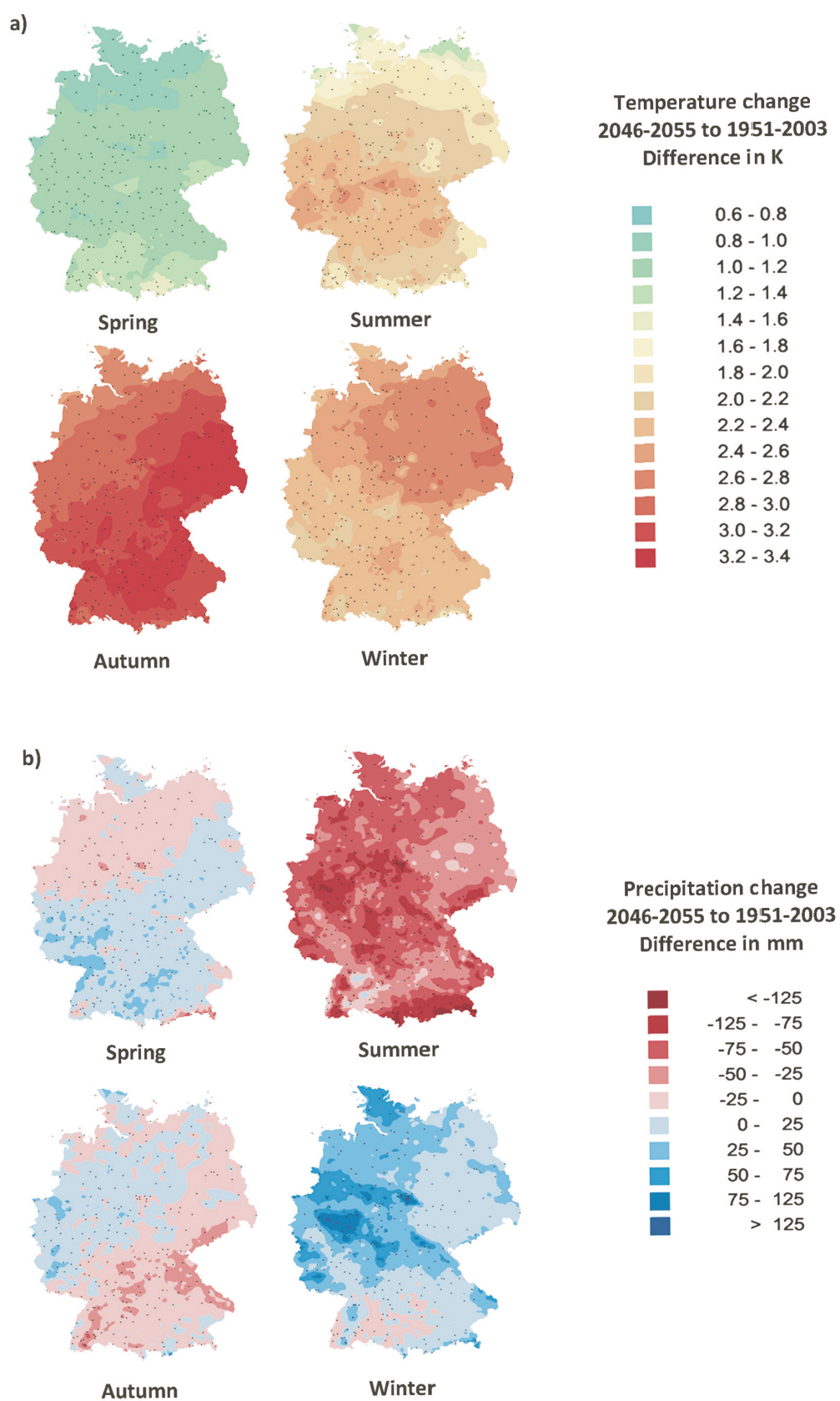
3.2 Exposure

Regionalised climate change projections for Germany (models: REMO, WETTREG, CLM) suggest, on the basis of IPCC SRES scenario A1b, a significant temperature increase until 2055 (Figure 3a; after Stock, 2008). Temperature will rise especially in autumn and winter, ranging from 0.6 to 3.4 K. An extension of the vegetation period amounting to two weeks can already be observed in Central Europe (Menzel, 2006), and a further advance of bud burst and flowering due to warming is expected for the future. Additionally, the frequency and severity of winter and late frosts are expected to change. Model projections for precipitation reveal a shift in seasonal distribution (from summer to winter) and less continuous but more intense rain (Figure 3b). Although there will be regions in Germany with decreasing and others with increasing precipitation sums (Stock et al., 2009; Becker et al., 2008), the probability for summer droughts and heat waves is likely to increase considerably throughout the country.

3.3 Sensitivity

To analyse potential impacts of changing climate variability and extreme events on tree growth and vitality, dendro-ecological approaches have shown to be a strong tool (e. g. Büntgen et al., 2008; Schweingruber, 1996). For Germany, there is increasing evidence that trees suffer more from summer droughts. Schröder (2009), for example, found an accumulation of negative pointer years in Scots pine (*Pinus sylvestris*) stands in northeastern Germany over the last two decades. Further, an analysis of intensively monitored observation plots (Level II network) reveals a significantly increased sensitivity of European beech (*Fagus sylvatica*) to climate variation since 1990 (Beck, 2011; Beck, 2009). High drought sensitivity of beech is also observed by other studies, whereas sessile oak (*Quercus petraea*) is found to be more drought tolerant (Scharnweber et al., 2011; Friedrichs et al., 2009). Species-specific drought sensitivity was also shown for an altitudinal gradient in southwestern Germany (van der Maaten-Theunissen et al., 2013). It was found that growth of Norway spruce (*Picea abies*) was negatively affected at all altitudes (400 to 1140 m a.s.l.), whereas growth of silver fir (*Abies alba*) responded to drought only at low altitudes.

Regional differences, local variation and temporal variability in drought sensitivity, as well as uncertainty in growth responses of trees to climate conditions that they were never exposed to before, make future estimates of forest growth difficult. Moreover, the response of tree species to climate variables is often analysed and described for pure stands only. The question whether tree species-rich forests modulate drought stress still remains poorly understood. In mixed

**Figure 3**

Projected changes in (a) temperature and (b) precipitation sums for Germany (A1b scenario) after Stock (2008). Trends in temperature and precipitation sums are calculated as the difference between 2046 to 2055 and 1951 to 2003, and are presented for spring, summer, autumn and winter.

stands, under specific circumstances, admixed species can increase drought resistance of the main tree species. The admixture of oak and Norway spruce in beech stands, especially on productive sites, for example, was found to reduce competition among beech trees. Thereby, oak mitigates the drought sensitivity of beech over effects of hydraulic water lift, whereas spruce changes the structure of beech stands, allowing more light to come in (Pretzsch et al., 2013; Pretzsch, 2009). In a gradient study across Europe, however, Grossiord et al. (2014) also found that drought resistance can be lowered by mixing other tree species, especially in drought-prone areas, which points to the fact that the adaptive capacity of forests is not always increased by high tree species diversity.

Studying biotic and abiotic disturbances becomes increasingly important as well with contemporary changes in climate. Pests and other damaging agents can be affected directly, e. g. by accelerating their reproduction rates, or indirectly by weakening the vigour of their host plants. There is evidence that forests in Central Europe have increasingly suffered and will further suffer from pests, diseases as well as from new pests that have not been a problem before, e. g. pine wood nematode (*Bursaphelenchus xylophilus*) or agents of ash decline (*Chalara fraxinea*) (Bolte et al., 2009). An increasing amount of timber had to be harvested due to mortality over the last years. Salvage cuttings following oak decline in Brandenburg, for example, increased from about 6000 m³ in 1995 to 13.000 m³ in 2004 (Möller et al., 2006). In Baden-Württemberg (southwestern Germany), an average level of salvage cutting of around 30 % is reported for the total forest area during the period of 1986 to 2011. This is especially due to increased risks associated with the management of Norway spruce in age-class forests, i. e. storm, drought and biotic disturbances (Schröter et al., 2012). The situation in Austria is quite similar, where Norway spruce is the dominating tree species as well: 19 % of the annual cut is salvage cutting for large forest owners (> 200 ha), compared to 14 % for small-scale forest owners (Büchsenmeister and Gschwantner, 2013, for the time period 1981 to 2009). Nevertheless, it should be mentioned that salvage cuttings are enhanced by record high standing volumes in German (and European) forests (European Commission, 2011; Oehmichen et al., 2011). Finally, forest fire has emerged as an increasingly important disturbance agent. In Brandenburg the number of fires rose in the past 20 years to around 500 occurrences per year, following dry episodes like in the years 1976, 1992 and 2003 (Badeck et al., 2004). Fire hazards are expected to increase further in the future (Lasch-Born et al., 2015; Gerstengarbe et al., 2003).

3.4 Adaptive capacity

Adaptive capacity of trees can be determined on the level of individual trees and (or) populations. On the level of individuals, plants can respond to environmental stresses with decline (mortality) or phenotypic plasticity (short-term response; Nicotra et al., 2010; West-Eberhard, 2003). Populations, on the other hand, can adapt via evolutionary

adaption, e. g. due to selection processes (long-term response; Aitken et al., 2008).

There is extensive literature on short-term stress response (stress concepts) of plants, such as the production of compatible solutes to stabilize the water potential of the plant after drought, cold or salt stress (Schulze et al., 2002). Substances in needles and leaves, which respond sensitively to environmental changes, can be used as proxies for environmental stress (biomarker analysis, see Kätzel, 2003). Besides, wood anatomical features can be studied, since trees continuously adapt to changing environmental conditions by adjusting their hydraulic system (conduit size and pit structures, Fonti et al., 2010). Lastly, morphological parameters such as root area or the root-to-shoot ratio can be analysed, as they are considered adaptive traits, especially in response to drought (Fonti et al., 2010).

Selection processes on the population level as a consequence of extreme events may lead to lower genetic differentiation due to directional adaptation on specific environmental factors (Hampe and Petit, 2005). The assessment of genetic variation within populations, before strong selection takes place, is therefore of fundamental importance for valuing their adaptive capacity (see section 4 on adaptation options).

3.5 Vulnerability assessment

A qualitative assessment on the vulnerability of tree species and regions to changing environmental conditions takes into account sensitivity and adaptive capacity of tree species and forest stands (Kreft et al., 2013). In Germany, Norway spruce is considered as the most vulnerable tree species, as spruce was widely planted in monocultures outside of its natural range that frequently lack a species-site match (van der Maaten et al., 2009). Moreover, European ash and oak show signs of decline on many sites throughout Germany (Möller, 2009). Concerning the spatial variability of vulnerability, regions such as the Berlin-Brandenburg (capital) area and parts of the Rhine valley are estimated to be highly vulnerable areas due to already low precipitation and unfavourable soils with low water storage capacity (Stock et al., 2009; Zebisch et al., 2005).

4 Adaptation options and their compatibility to CNS

Vulnerability assessments (see chapter 3.5) allow the formulation of adaptation strategies and options. Thereby, one may distinguish between passive and active adaptation (Millar et al., 2007). While passive adaptation is based on the use of forest succession (reduction of silvicultural input), active adaptation entails the use of silvicultural methods (e. g. tending, thinning, stand conversion) to change stand structures and composition in a way that the resulting forest is better adapted to climate change (Bolte et al., 2009). Among possible silvicultural options to implement adaptation such as the increase of tree species richness and genetic

diversity of forests, the reduction of biotic and abiotic risks, actions in forest operations, and others (cf. Bolte et al., 2009; Spittelhouse and Stewart, 2003), this review focusses on increasing

- 1) tree species richness and structural diversity, and
- 2) genetic variation of tree populations (Figure 4).

In sections 4.1 and 4.2 it is explored whether these adaptive forest management options are compatible with CNS (see also Brang et al., 2014 for an overview on diverse adaptation principles).

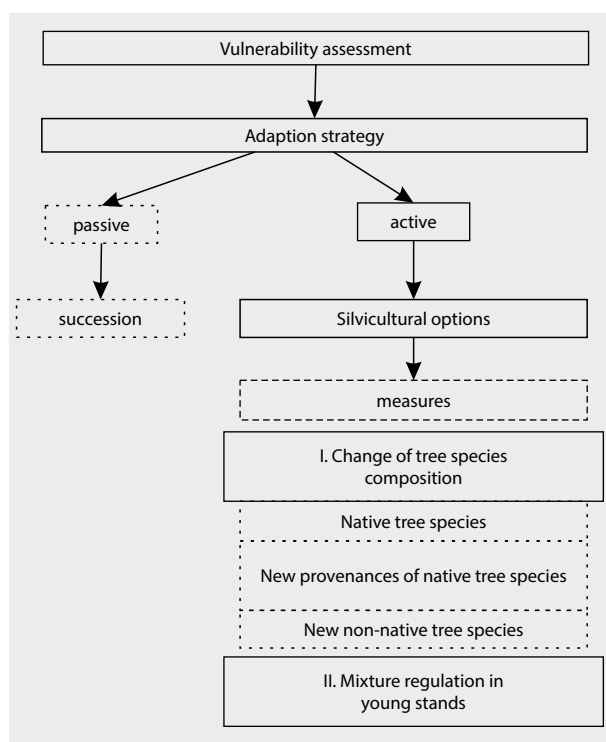


Figure 4

Flow chart for silvicultural adaptation options.

4.1 Increase of species richness and structural diversity

The question how biodiversity affects the functionality of a forest ecosystem is of high relevance (functional biodiversity research, Scherer-Lorenzen, 2011). Here, a lack of research is obvious and it remains difficult to forecast the effect of mixtures in dependence of site and forest function (Pretzsch, 2009). However, some first results can be mentioned. With an increase in species richness, compared to monoculture stands, the possibility to include tree species with sufficient fitness in the face of climate change is enhanced. Species-rich tree populations often contain plants with different 'strategies' concerning establishment and competitiveness (plant functional types, according to McArthur and Wilson, 2001). Thus, resources such as light, water and nutrients can be spatially and temporarily used in a different way. In many cases, species-rich forests are thus more productive than less diverse forests (Pretzsch et al., 2010).

Recent vegetation function analyses support the finding that more 'complex', mixed forests with old-growth features show a higher stress tolerance¹ than homogeneous, intensively managed forests with a high level of disturbances and timber extraction (Norris et al., 2011). Stress-tolerant species (S) as well as competitive species (C) can be found in complex resilient ecosystems, whereas the ruderals (R) occur in more simplified and disturbed systems. Following this, the establishment of monospecific and unilayered coniferous stands dominated by ruderals (R) counteracts forest adaptation to (future) environmental stress, since S and R strategy are mutually exclusive. Therefore, climate change impacts can be buffered more successfully in a forest with a high capacity to respond to different disturbance agents, i.e. a forest with a high amount of stress-tolerant species which easily regain pre-disturbance functionality (Drever et al., 2006).

Furthermore, species richness in forests can lead to positive effects on soil water availability, compared to pure conifer stands (Mitscherlich, 1971). This is crucial, as water shortage will likely affect many forest ecosystems in the future. Although studies on the effect of species mixture on soil water availability are rare, there is evidence that interception losses are higher in pure conifer stands with Scots pine and Norway spruce compared to broadleaved or mixed stands with European beech (Barbier et al., 2009; Berger et al., 2009). In a study in northeastern Germany, Müller (2009) found that mixtures of Scots pine with European beech attained higher seepage rates compared to pure Scots pine stands. This positive effect is due to reduced interception losses and a higher stemflow on broadleaved trees compared to pine. Moreover, in pure (pine) stands the often thick ground vegetation layers lead to a further reduction of soil water with the negative consequences on tree transpiration and growth (Müller and Bolte, 2009).

Structural diversity in forests encompasses different age cohorts and size classes of trees and the spatial arrangement of different stand types on landscape level and structural elements such as large living and dead trees, coarse woody debris or seed producing tree clusters on stand level. These stand legacies provide essential ecosystem processes (e. g. seed dispersal, nutrient translocation) and preserve genetic information in the phase of an ecosystem's recovery after disturbance. They are important elements in the reorganization loop of the adaptive cycle (Bauhus et al., 2009; Drever et al., 2006). Moreover, stand legacies contribute as important habitat to faunal species richness, e. g. as antagonist species which can curb biotic disturbances and thus reduce forest vulnerability.

Compatibility to CNS and recommended measures

Generally, CNS provides mixed forests which in case of complementary species mixtures enhance adaptive capacity of forests (Pretzsch et al., 2013). However, an application of

¹ Stress tolerance according to Grime (1974) means adaptation to unfavorable environmental conditions and disturbances.

silvicultural systems towards small-scale interventions narrows the tree species composition towards a mixture of mostly shade tolerant species. Where mixed stands already exist, the maintenance of species diversity in forests is fundamental. Special emphasis should be laid on rare tree species, which are likely to increase a forests' capacity to respond to diverse disturbance agents. Where pure 'high-risk' stands occur, e. g. overstocked Norway spruce stands on unfavourable sites, a conversion into site-adapted and more resilient mixed forests should be considered. Over the last two decades, forest conversion has been a common strategy in Germany to restore more 'natural' forests at large scale by increasing the share of tree species of the natural forest cover. Norway spruce or Scots pine plantations, not suited for the respective sites, are underplanted with broadleaved tree species to create more stable and multifunctional forests for the future (Spiecker et al., 2004). According to the third National Forest Inventory in Germany (Thünen-Institut, 2015 – BWI 2012), already 76 % of the forest land (all ownerships) is occupied by mixed stands where at least 10 % of another tree species is admixed (Thünen-Institut, 2015).

Structural diversity is highly compatible with CNS. This supports the application of silvicultural systems with retention components (individuals or patches of hold-over trees) and old-growth attributes such a significant amount of dead-wood (Bauhus et al., 2009).

4.2 Increase of genetic variation

Genetic variation of plant populations is a consequence of population size and genetic differentiation. Mutation and selection enable a successive adaptation of populations to specific environmental conditions. On-going differentiation for long periods of time allows the establishment of specific population traits (so-called ecotypes; McArthur and Wilson, 2001). Therefore, populations from refugial ranges (rear edges of species ranges) often show a higher genetic variation than more central populations (Hampe and Petit, 2005). For example, a higher genetic variation was shown for European beech in three southern European refugia compared to the Central European species range (Comps et al., 1998).

The genetic variation within tree species and between populations (measurable by the frequency of alleles and genetic difference) is a precondition for the adaptive capacity of forests (Kätzel, 2010; Hamrick, 2004). On an individual level, the more variable the genetic response norms of trees to environmental factors, the higher the number of adaptation options will be. Moreover, in populations with a high genetic variability, traits of trees which constitute advantages concerning changing environmental conditions (i. e. adaptive traits) can more easily be developed in the process of evolution than in genetically narrow populations (Kätzel, 2010; González-Martínez et al., 2006). Further, the strategy of sexual reproduction of trees very much determines the velocity of adaptation (Kätzel, 2010). A high seed production rate, short generations and ample seed dispersion enhance the chance of genetic variation on stand level and thus give

pioneer species a significant advantage in adapting to fast environmental changes. Hence, natural forest regeneration profits from a high variety of mother trees and a long-term regeneration process. Planting can be an option to enrich the genetic pool of populations, especially if plants with verified genetic variation are used. In this respect, especially provenances of tree species at range boundaries might be important sources for ecotypes with specific adaptive traits (Bolte et al., 2007). In Germany, for example, drought and frost tolerance are becoming increasingly important traits with projected changes in climate. For beech and oak, which are the major broadleaved tree species used for conversion of coniferous forests, ecotypes from eastern range boundaries are promising, as the frequency of drought and frost events increases with continentality (Rose et al., 2009).

As adaptive traits of trees are often under multigenic control, efficient tools to identify and understand the adaptive variation in tree populations are urgently needed. A severe constraint in the past was that with current state-of-the-art marker techniques such as isoenzyme and DNA marker, only a small number (20 and 150, respectively) of mostly non-adaptation relevant genetic locations could be analysed. In the future, however, sequencing and association mapping at candidate genes for adaptive traits (QTL technique) may provide more valuable information on adaptive capacity of trees (e. g. González-Martínez et al., 2006).

Compatibility with CNS and recommended measures:

In general, the measures comprising an increase in genetic variation of tree populations fit well into the concept of CNS.

In addition to long-term natural regeneration, a promising way could be the use of enrichment planting, e. g. with drought stress tolerant plants (Kolström et al., 2011). This inclusion of ecotypes (provenances) via assisted migration from regions where future climate patterns already exist is an important measure to increase adaptive capacity of forests. However, one may pay attention on other traits such as quality that could be inferior compared to local ecotypes (Kätzel and Löffler, 2007).

5 Conclusions

Two main conclusions can be drawn from this review on vulnerability and forest adaptation needs to climate change for the case of Germany and CNS.

- 1.) An increase in species richness increases the variety of response norms which enhances the probability of the forests to resist or compensate for disturbances or the negative effect of extreme climatic events.
- 2.) For the development of an ecosystem towards increased adaptive capacity it is essential to enlarge the genetic variability of tree populations. Thus, the probability of the establishment of new adaptive traits can be raised, especially when species with high production rates and extensive seed dispersal are included. On the individual tree

level there is a need to improve the plant's stress tolerance against climatic stressors, e.g. summer drought or late frost.

Regeneration phases are essential 'windows of opportunity' for forest adaptation. Variable types of regeneration cuts (single-tree selection, group selection and shelterwood) allow for a broad range of different species (and survival strategies) to regenerate and thus to enhance stand resilience. These regeneration systems emulate quite a significant part of possible natural disturbance events. However, the restrictions of CNS for the use of natural regeneration and 'low impact' interventions and the focus of CNS systems on mid- and late-successional tree species limit the options for human-induced assistance of adaptation, e. g. by introducing non-native or specific drought-resistant tree species and provenances, respectively or by applying extensive site preparation methods (small clear cuts included).

Acknowledgement

This review paper is linked to activities conducted within the COST Action FP1106: STReESS – Studying Tree Response to extreme Events: a Synthesis.

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