Ciência Florestal

ISSN 1980-5098
OPEN ACCESS

Ci. Fl., Santa Maria, v. 35, e90715, p. 1-16, 2025 • https://doi.org/10.5902/1980509890715
Submitted: 29th/01/2025 • Approved: 4th/02/2025 • Published: 14th/02/2025

Review Article

Continuous-cover forestry – the appropriate concept for climate change adaptation of forests in Germany?

Silvicultura de cobertura contínua – o conceito adequado para a adaptação das florestas às mudanças climáticas na Alemanha?

Peter Spathelf[I]
Andreas Bolte[II]

[I]Eberswalde University for Sustainable Development, Eberswalde, Germany
[II]Thünen Institute for Forest Ecosystems, Eberswalde, Germany

ABSTRACT

Continuous-cover forestry (CCF) is a largely coherent strategy for adapting to climate change, in particular if it is following the concepts of adaptive forest management (AFM). The key is to distribute and reduce the risk of disturbance. A mixture of tree species and provenances with high functional diversity are the most important levers. Active adaptation is most relevant in young forests and where specific ecosystem services are pursued. However, the following measures serve to improve the presented silvicultural approach and should be given particular attention, among others the use of diverse forms of regeneration, the consideration of non-native or non-local tree species and provenances, and the creation of sufficient attributes from natural, unmanaged forests.

Keywords: Continuous-cover forestry; Climate change; Adaptive forest management; Germany

RESUMO

A silvicultura de cobertura contínua (CCF) é uma estratégia amplamente coerente para a adaptação às mudanças climáticas, principalmente se estiver seguindo os conceitos do manejo florestal adaptativo (AFM). A chave é distribuir e reduzir o risco de perturbação. Uma mistura de espécies de árvores e procedências com alta diversidade funcional são as alavancas mais importantes. A adaptação ativa é mais relevante em florestas jovens e onde serviços específicos de ecossistema são buscados. Entretanto, as medidas a seguir servem para aprimorar a abordagem silvicultural apresentada e devem receber atenção especial, entre outras, o uso de diversas formas de regeneração, a consideração de espécies e procedências de árvores não nativas ou não locais e a criação de atributos suficientes de florestas naturais não manejadas.

Palavras-chave: Silvicultura de cobertura contínua; Mudança climática; Manejo florestal adaptativo; Alemanha

1 CONTINUOUS-COVER FORESTRY AND CLIMATE CHANGE – HOW DOES THIS FIT TOGETHER?

The origins of the concept of natural forest management date back to the 19th century. Karl Gayer, a professor of silviculture at the University of Munich, propagated the idea of mixed forests in groups in order to increase the forest's resistance to disturbances such as insect calamities. At the beginning of the 20th century, Alfred Möller gave an important impetus to natural forest management with his idea of Continuous-Cover Forestry (CCF – the German term is 'Dauerwald'). He regarded the forest as an organism that should be managed carefully, above all as a mixed forest without clear-cutting while preserving soil fertility (Spathelf *et al*., 2016). Möller's impact was initially limited and he was unable to achieve a breakthrough for his concept. Although the idea was still well known, it was marginalized by representatives of mainstream forestry (age-class management with pure stands). After the political upheavals caused by the Second World War, a small, exclusive association of forest owners who were convinced of Möller's idea was formed in the western part of Germany through the 'Arbeitsgemeinschaft Naturgemäße Waldwirtschaft' (ANW). In the German Democratic Republic, the guiding principles of nature-based forestry were also taken up and put into practice in the early 1950s. A convergence of nature-based forestry with the previously age-class-oriented pure stand management, in particular of state forests (in the Federal Republic of Germany), took place from the 1980s and 1990s onwards. The reasons for the large-scale conversion of pure stands of the same age into near-natural forests were so-called 'forest dieback' and other disturbance events such as storms, which severely affected the age-class forests, and the increased environmental awareness of the population with the emergence of an environmental movement (European Year of Nature Conservation 1970). Today, there are only marginal programmatic silvicultural differences among the forest owners in Germany, above all in the use of clear-cutting, which is not completely excluded especially by some private forest owners (Brang *et al*., 2014; Spathelf, 1997).

Important principles of nature-based forestry are therefore (selection, according to Anw Deutschland, 2013):

- The principle of 'forest before game' applies; naturally occurring vegetation must be able to develop without artificial protection measures;
- Maintenance of ecosystem stability through the establishment of site-adapted, structurally-rich mixed stands;
- Avoidance of clear-cutting;
- Stand interventions as a permanent process to optimize the quality, growth and vitality of valuable individual trees;
- Forest regeneration, where possible through natural regeneration;
- Protection and, if necessary, improvement of the yield potential of the site through a mixture of site-adapted tree species, a permanent canopy cover and machine driving only on permanently created, marked logging roads

CCF and its variants such as 'retention forestry' are being promoted worldwide as alternatives to the clear-cutting systems that have prevailed for a long time (Puettmann *et al*., 2015).

2 ON THE EXTENT OF CLIMATE CHANGE

Germany is experiencing by far the fastest climatic change since the last ice age. Overall, a climatic shift in mean temperature values can be assumed, with an increase in the range between minimum and maximum temperatures. With precipitation remaining roughly the same overall, a reduction in precipitation during the vegetation period is also assumed. Together with an accumulation of extreme weather events (e.g. so-called hot droughts, i.e. combinations of dry periods and heat waves with correspondingly high evapotranspiration rates), years with drought stress for our forest trees can be expected more frequently by the end of the century than was previously the case. However, frost events (late and winter frosts) will probably continue to occur. Accordingly, we cannot assume a change in climate to a Mediterranean or subtropical climate in which frost events are absent, but rather a continentalization with greater temperature ranges between cold and heat extremes or even a new type of climate (IPCC, 2021).

3 IMPACT OF CLIMATE CHANGE ON FORESTS

Climate change has a direct impact on trees through heat and drought, which can currently be observed on pine trees in Brandenburg since 2015. Extreme temperatures of over 40 °C were recorded which triggered dieback processes in many trees. In the case of spruce, the combined effect of abiotic (e.g. storms) and biotic factors (e.g. bark beetles) is known from numerous regions in Germany and has already led to considerable amounts of damaged wood and large cleared areas for many years. The shifting of tree species ranges due to drought stress poses a threat to all the major economically relevant tree species. This is already now the case in numerous dry inner-Alpine valleys in Switzerland and Italy, where Scots pines at the edge of their natural range are dying off in a complex disease process and are gradually being replaced by downy oaks (Rigling *et al*., 2006). In the lowlands of northern Germany, a decline in forest productivity is to be expected due to excess tree mortality. Model calculations with the ForClim simulator confirm a similar trend for Switzerland (Bircher *et al*., 2016). Potentially associated with the change in tree species from spruce or pine to possibly sub-Mediterranean deciduous tree species is a decline in economic yield (Wessely *et al*., 2024; Hanewinkel *et al*., 2013).

The situation of the forest after these disturbances is precarious in many places. A key question is which silvicultural concept will succeed in adapting to climate change. Is the widely accepted CCF robust enough in the face of rapidly changing climatic conditions?

4 MANAGEMENT OPTIONS FOR FOREST ADAPTATION TO CLIMATE CHANGE

Adaptation refers to all ongoing processes that lead to forest ecosystems adapting to changing environmental conditions. Adaptive capacity, on the other hand, is the future ability to adapt to unfavourable changes in the environment either morphologically and physiologically in the short term on the basis of the individual tree, or, in the long term, evolutionarily through selection at the population level.

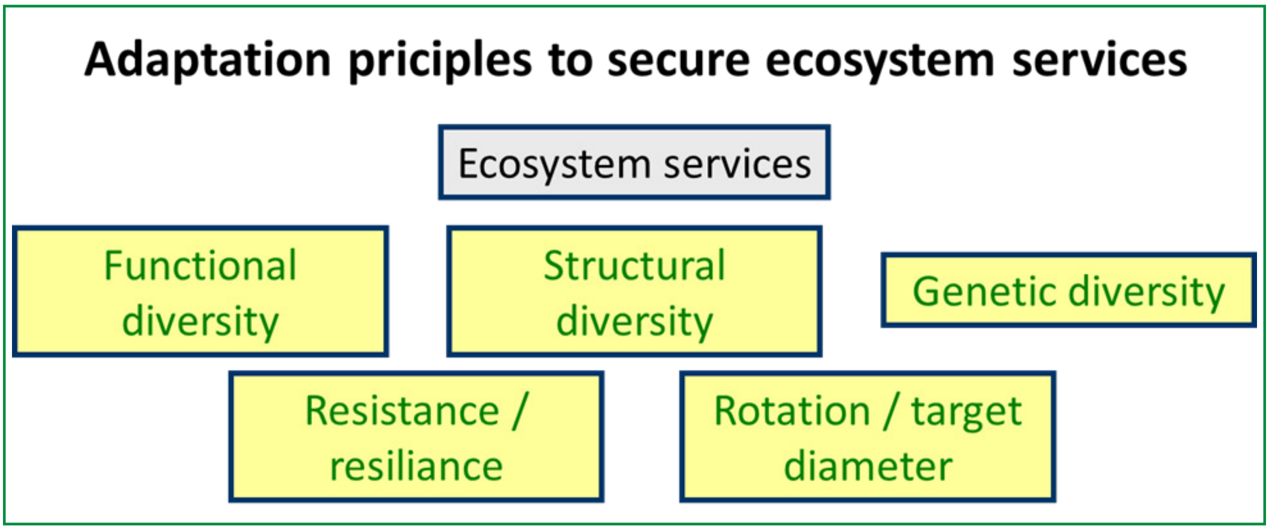
Adaptation can occur passively by allowing forest succession or actively by managing or reshaping forest ecosystems with the aim of providing certain ecosystem services (Spathelf; Bolte, 2020; Bolte *et al*., 2009).

To clarify the question of whether CCF is a suitable silvicultural concept in times of climate change, five principles were identified and examined for their compatibility with adaptation (Brang *et al*., 2014; Figure 1):

1. promotion of tree species richness
2. promotion of structural diversity
3. promotion of genetic diversity
4. strengthening the resistance and resilience of trees
5. reduction of the rotation period and/or the target diameter

Silvicultural measures such as regeneration felling, planting, natural regeneration or thinning can each address one or more principles.

Figure 1 – Adaptation principles and silvicultural measures adapted to them



Source: Brang *et al*. (2014)

A central starting point for strengthening the resistance and resilience of forests is the promotion of tree species mixtures. According to the fourth German National Forest Inventory (BWI 2022), 21 % of forest stands across all ownership types in Germany are still pure stands. Pure spruce and pine stands in particular are due to be converted into structured mixed forests in the coming decades. In addition, there are 600 thousand hectares of cleared areas in calamity areas of considerable size that need to be reforested (BMEL, 2024).

Meta-studies show that tree mixtures with a functional diversity of tree species are favourable for the resistance and resilience of stands to the negative effects of climate change. The processes involved are, on the one hand, competition reduction and facilitation (Pretzsch *et al*., 2020). For example, mortality studies of spruce and beech show a higher probability of survival (due to higher resistance, but also resilience) in mixtures compared to the respective pure stands. It has been observed that beech in mixtures with spruce adapts its root system and reaches into deeper soil layers to supply itself with water (Bolte; Villanueava, 2006), leading to a facilitation of beech fine rooting compared to pure beech stands (Bolte *et al*., 2013). In turn, spruce in such mixtures with beech leads to a reduction in competition with beech leading to a considerable overyielding of spruce mixed with beech compared to pure spruce stands (Pretzsch; Schütze, 2009; Pretzsch, 2022). In the investigation of radial growth after dry years in areas of the Biodiversity Exploratories (large-scale long-term study areas of biodiversity research), it was shown that beech showed better growth in mixtures with, for example, pine or other deciduous trees than in pure beech stands (Annighöfer *et al*., 2017).

The most important time window for diversifying forest composition is regeneration. In retention systems, natural regeneration or advanced growth is already sufficiently established during the forest tending phase. While shade-bearing tree species can easily establish themselves under the canopy of an old stand, light tree species require patchwise openings, at least for their further development. Natural regeneration secures locally adapted species. However, as the natural migration speed of tree species is too slow under rapidly changing environmental conditions, enrichment with planted tree species with specific adaptive traits is an option. In particular, provenances from the southern part of distribution areas (rear edge) or even from completely other geographical origins can have desirable adaptation properties, e.g. against drought stress (e.g. beech: Stojnic *et al*., 2018; Bolte *et al*., 2016), and provide with their growth a considerable carbon sink potential maintaining or even increasing the carbon sink of European forests (Chakraborty *et al*., 2024; Buchacher *et al*., 2020). To supplement the tree species portfolio, native tree species with rarer occurrences (so-called secondary tree species) are initially suitable. These include numerous native deciduous tree species such as hornbeam, small-leaved lime, Norway maple and field maple, wild service tree and wild cherry. Some of these mostly less competitive tree species are more resistant to drought stress than the native European beech (Kunz *et al*., 2018; Roloff & Grundmann, 2008) or respond more resiliently to drought stress

(Bauhus *et al*., 2017). Moreover, forest tending can significantly influence tree species mixtures in favour of desirable species. So-called non-native or exotic tree species can be integrated to a small extent into mixtures with native tree species. Many of these exotic species, such as Douglas fir, grand fir, red oak and Japanese larch, have proven their adaptability in north-eastern Germany. They perform well, rejuvenate naturally and have an overall acceptable risk (Lockow, 2004). Disadvantages include the lower habitat quality, invasiveness in some cases (e.g. black locust and black cherry) and a lack of suitable seed. In any case, the participation of non-native tree species should be carefully examined and only recommended in combination with native tree species on small areas.

Expanding the tree species and provenance portfolio during forest regeneration is the central strategy for climate change adaptation, as it increases flexibility in the face of disturbances.

The resistance to disturbance in structured continuous-cover forests results from the diversity of structural elements (horizontal, vertical, occurrence of different forest development phases, 'patches'), stable individual trees and low stocks compared to age-class forests.

The advanced regeneration of stands considerably increases the variety of silvicultural options, especially after storms or other damaging events. An additional stand layer is then present, covering the forest floor and preventing the establishment of grass cover with negative consequences for the development of mouse populations and the use of scarce soil water. However, it should be noted that the advanced regeneration should not necessarily occur everywhere in the stand, but rather irregularly, containing light tree species as well as shade-bearing species. An important measure to increase the resilience of forests is to leave remnants of the previous stand in the form of old and large trees and deadwood in various stages of decomposition (standing and lying). These attributes of natural forests, known as 'stand legacies', lead to diverse micro-structures and thus habitats for a variety of organisms, which in turn act as antagonists of insect pests (Larsen *et al*., 2022). Nevertheless, there is also evidence that old (and high) trees are more prone to water supply collapse due to decreased drought tolerance (Mcgregor *et al*., 2020) and to windfall (Ni Dhubhain *et al*., 2001) than young trees.

Such structurally rich forests show a broad congruence with the dominating disturbance regime in temperate mixed European beech stands, enhancing their adaptive capacity. This silvicultural approach recently was called Natural Dynamics Silviculture (Nds; Aszálos *et al*., 2022).

Genetic diversity is a key parameter for increasing the resistance and resilience of forest stands. In particular, large metapopulations with different ecotypes (i.e. subpopulations with differentiated, ecologically effective characteristics) have a good chance of adapting to changing environmental conditions. As evolutionary adaptation processes in populations cannot keep pace due to the speed of environmental change, the planned migration of ecotypes (provenances) or species to areas with suitable climates is of great importance as an adaptation strategy. This approach is known as 'assisted migration'. According to Williams and Dumroese (2013), there are basically three possibilities: 1. the translocation of provenances within a species range from south to north, 2. the expansion of a species range, such as the downy oak, from the already sub-Mediterranean area of Central and Southern Europe to the north or northeast, and 3. the establishment of a species far from its natural range, as is the case with e.g. Northern red oak, which originates from the central hardwoods in the Appalachian mountains (USA) and has been successfully cultivated in Germany for around 100 years.

'Assisted migration' enables the enrichment of native forests with drought-tolerant species and provenances or with species and provenances that have specific adaptive traits. It thus serves to maintain productive forests in times of climate change. The disadvantages of this approach include the risk of an ecotype or tree species becoming invasive in its new habitats and the introduction of potential pathogens together with the migrated species or provenances (Pötzelsberger *et al*., 2020; Buchacher *et al*., 2020).

Strengthening the resistance and resilience of trees is a central concern in the adaptation of forest stands to climate change. Forest management measures can enhance the vitality of trees (crown dimension, needle and foliage density) - at least in the medium to long term. As early as 1986, Spiecker demonstrated in plenter forests in the Black Forest that long-crowned silver firs recovered more quickly after drought stress (e.g. 1976) than short-crowned individuals. The crown dimension (crown ratio), in turn, is closely correlated with a tree's standing space, usually through the application of forest management measures. In experiments with spruce trees, it was shown that, compared to a weak thinning, a strong thinning leads to a relaxation of the water balance in the soil (Sohn *et al*., 2016; Kohler *et al*., 2010).

This principle is also consistent with CCF, which attaches great importance to continuous stand interventions and thus the development of vital trees.

In general, the risk of storm damage and drought stress increases with tree age. With regard to storm damage, there is a clear correlation between stand height (and thus tree age) and storm damage risk (Albrecht *et al*., 2013). In the case of drought stress, the relationships are somewhat more complex. With increasing tree height, the risk of water supply collapse ('hydraulic failure', Barigah *et al*., 2013) increases, especially in anisohydric species (i.e. tree species that do not respond sensitively to drought stress by closing their stomata, but in which the water potential decreases accordingly due to further transpiration) such as European beech. Here too, CCF with a focus on growth control assures that thick (and potentially valuable) trees can be grown in a reasonable period of time.

5 ADAPTIVE FOREST MANAGEMENT (AFM) AS A PRE-REQUISITE FOR FUTURE RESILIENT FORESTS?

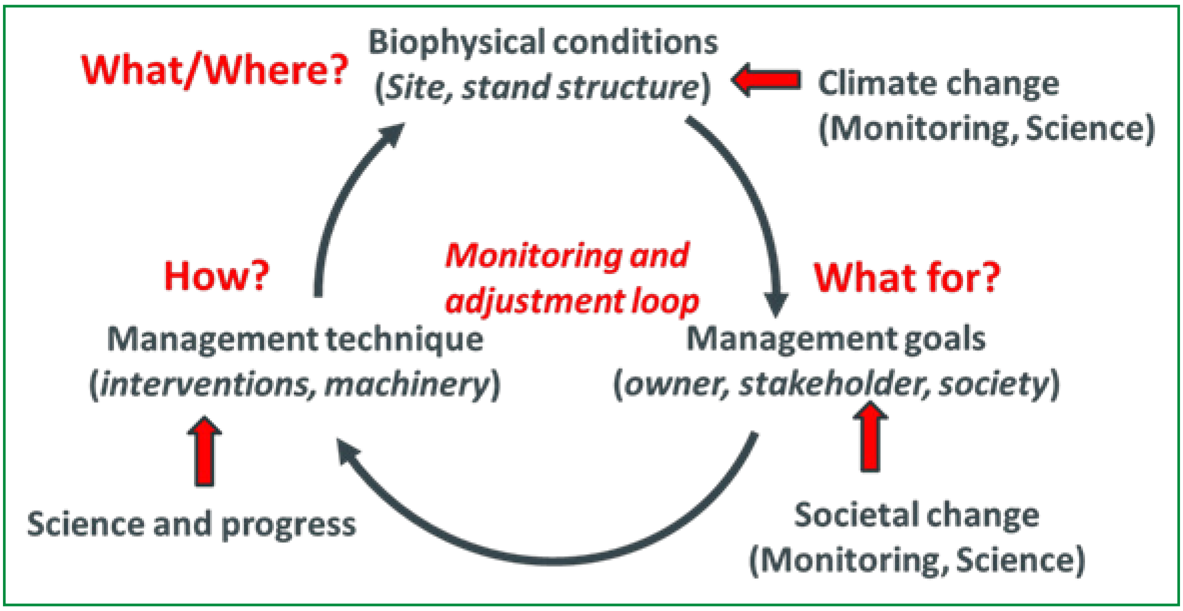
In order to create the forest of the future, increased efforts are required in the area of forest conversion. The 'key situation' of forest regeneration should preferably be used to establish diverse stands. This involves a thoughtful combination of natural regeneration (succession) with supplementary planting or sowing. In the lower-lying and warmer areas (below 600 m asl), the focus is increasingly on the task of preserving forests in order to secure the ecosystem services that are in demand. To this end, forests should be converted into continuous-cover forests, preferably with the participation of deciduous tree species (oak, beech and less common native tree species, including pioneer tree species).

At higher altitudes (montane to high montane levels), productive mixed conifer forests could be managed, including spruce, where suitable for the site and stable in the long term, but also silver fir or Douglas fir.

In many places, the excessive density of browsing game is still the greatest obstacle to the development of diverse continuous-cover forests.

Adaptive forest management (AFM) is a suitable management approach for managing forest resources in the face of uncertain knowledge and rapid environmental changes. AFM follows the principle of 'improving of management [...] by learning of their outcomes' (Ellis *et al*., 1997). A recent AFM concept (see Fig. 2, Bolte; Sanders, 2021) is based on a frequent feedback loop adjusting management to changing forest ecosystem status or structure and varying goals. This loop is meant to be flexible in time, but loop frequencies may be aligned with typical planning horizons, i.e., between five years and 20 years. AFM efforts should include frequent monitoring and adjustments of three components (1) biophysical conditions ("what?"), (2) management goals ("what for? /why?"), and (3) management techniques ("how?", Figure 2). All three components are not static, but dynamic and variable. The biophysical conditions include monitoring approaches focusing on environmental conditions for growth, survival and reproduction of the forest ecosystems and the forest composition and structure themselves; climate change is a major factor leading to increased variability of these conditions. The management goals are determined by forest owners, stakeholders and the society. With this, AFM provides a broader concept of future forest adaptation where continuous-cover forestry can play a decisive role for its implementation.

Figure 2 – Adaptive forest management (AFM) scheme



Source: Bolte, Sanders (2021)

6 CONCLUSIONS

The following measures are recommended as management options to keep CCF compatible with climate change adaptation:

1) Use of diverse forms of regeneration;

2) Consideration of non-native or non-local tree species and provenances;

3) Creation of sufficient attributes from natural forests / unmanaged forests;

4) Irregular thinnings and canopy openings to increase the structural diversity and tree species diversity (light demanding and shade-tolerant species), and;

5) Frequent monitoring and management variation if needed to adjust to climate and site dynamics, as well as management goals.

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Authorship Contribution

1 Peter Spathelf

Forest Engineer, Doctor in Forestry Sciences, Professor

https://orcid.org/0000-0002-0668-2319 • Peter.Spathelf@hnee.de

Contribution: Conceptualization; Formal analysis; Funding acquisition; Investigation; Project administration; Resources; Supervision; Visualization; Writing – original draft

2 Andreas Bolte

Forest Engineer, Doctor in Forestry Sciences, Professor

https://orcid.org/0000-0003-4106-0387 • Andreas.bolte@thuenen.de

Contribution: Conceptualization; Data curation; Investigation; Methodology; Software; Validation; Writing – review & editing

How to quote this article

SPATHELF, P.; BOLTE, A. Continuous-cover forestry – the appropriate concept for climate change adaptation of forests in Germany? **Ciência Florestal**, Santa Maria, v. 35, e90715, p. 1-16, 2025. DOI 10.5902/1980509890715. Available from: https://doi.org/10.5902/1980509890715. Accessed in: day month abbr. year.