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Executive Summary

This deliverable describes the interim status of the research in Task 2.4 concerning possible forest management options that could enhance the resistance of existing forest stands in Europe in relation to droughts. We focussed on three forest management options that are also in the focus of scientific and public discussions about forest adaptation to climate change:

1. Reducing stand density with thinning to ameliorate the resources availability in forests.
2. Maintenance or promotion of tree species diversity, as greater diversity of tree species and their interactions spread the risks and might buffer disturbance impacts on individual species. In this regard, we also covered to some extent structural complexity of forest stands as another important dimension of forest diversity.
3. Cessation of active forest management, which has been advocated for its potential to enhance resistance to disturbances, for example drought, by maintaining canopy integrity and thus beneficial microclimatic conditions.

Previously, the evidence base for answering this question was assessed from scientific literatures and available experimental data (milestones 4, 6 and 12). For the management option “thinning”, the evidence base was found to be sufficient to conduct a meta-analysis on the effect of thinning on drought-related tree mortality. The major result of this analysis was that thinning does not clearly reduce tree mortality after drought but it is also not exacerbating it, especially not in the case of dominant or co-dominant trees. This means that other positive effects of thinning, such as maintaining tree species diversity and encouraging advance regeneration, are not penalised by greater mortality. For the management option “tree species mixtures”, the evidence base was not strong enough to perform a quantitative, systematic review. Instead, we reviewed the most important publications on the topic as identified in the milestones and in a project meeting and stakeholder workshop in 2023. Overall, greater tree diversity has a predominantly positive effect on resistance to disturbances, namely drought, insect and mammal herbivory, wind but not fire which is an exception here. However, the effect is not universal and strongly depends on the identity of species in mixture, the type of disturbance as well as environmental conditions (site and climate). The evidence base for the effectiveness of “ceasing active forest management” to increase resistance to drought-related mortality was even weaker than for mixed-species forests. Therefore, given that a systematic review was not possible, we followed the same strategy and reviewed the most important publications. However, these provided only a scant information base. Accordingly, a first result is that more specific research on the effectiveness of management cessation/strict protection to increase stand-level resistance to disturbances is required. One hint from the reviewed literature is that forests that used to be managed and are now strictly protected are likely to be more vulnerable to disturbances.
The insights from reviewing the three management options above indicate that managing stand density, diversity and structure can potentially improve the resistance to drought in particular but also other disturbances compared to non-management. Active management interventions also offer additional opportunities to enhance the resilience of forest stands to disturbances. For example, in promoting advance regeneration through thinning or spread the infestation risk of pathogens by maintaining tree diversity, the potential for the remaining stand to recover from disturbances is fostered and the risk of stand-scale forest loss is reduced. Our review of the management options

underlined that their effectiveness in reducing drought stress is highly context-dependent. Additionally, coordinated research with standardized designs and methods would help to develop more robust management recommendations.

Keywords

Disturbance mitigation, drought-related mortality, resistance, resilience, thinning, mixed-species forests, unmanaged forests

1. Introduction

Placed in WP2 Task 2.4, this deliverable reports on potential stand-based forest management options to mitigate the effects of climate-change related disturbances on European forests. The focus of this work is on silvicultural measures to reduce the drought-related tree mortality, but other types of disturbance are also addressed.

A consequence of climate change is the occurrence of unprecedented disturbance regimes (Allen et al., 2015; Seidl et al., 2017), as was seen in the drought and heat wave that affected Central Europe 2018-2020 (Schuldt et al., 2020). Droughts will likely become more intense and more frequent and will happen ubiquitously (Allen et al., 2015). Droughts also work as pre-disposing factor promoting other types of disturbances, such as fires and outbreaks of biotic agents (pests and pathogens). With the loss in forest vitality as a consequence of droughts and other disturbances, important ecosystem services that the forests provide are also declining (Cantarello et al., 2017). To avoid this undesirable outcome, forest managers are looking for options to increase the resistance, resilience, and adaptive capacity of forests in the face of global change. While the need for active adaptation of forests is widely recognized among forest practitioners, there is also a great amount of uncertainty regarding the effectiveness of different adaptation options (Himes et al., 2023). Here we focussed on three stand-level forest management options that can be applied in existing forest stands to increase the resistance against drought-related mortality. Resistance is here understood as the capacity to withstand disturbance events. The management options we looked at were (1) thinning, (2) mixing tree species and (3) strictly protecting forests through cessation of management.

Thinning, is a common silvicultural practice aimed at reducing stand density and thus decreasing competition for trees and increasing their resource availability, including light, water and nutrients (Bottero et al., 2017; Sohn et al., 2016; Steckel et al., 2020). However, thinning opens the canopy and thus could lead to increased transpiration of individual tree crowns due to higher exposure to radiation and wind speed and more evaporation (Steckel

et al., 2020). Hence, the influence of thinning on drought stress of trees and mortality is likely context dependent.

Mixing tree species is a strongly advocated management option to adapt forests to global change (Messier et al., 2021). Whether it is suitable for enhancing the drought-resistance of individual species or the entire tree community will likely depend on the partitioning of resources through dissimilarities of functional traits of the species in mixture (Grossiord, 2020). For instance, different rooting depth can partition the access to soil water or differences in leaf phenology the access to light. Since trees of different dimensions also differ in their expression of traits and resource use (e. g. Dănescu et al., 2016), we analysed here the effect of structural diversity on drought-resistance as well.

Relying on the capacity of natural systems to self-regulate, passive adaptation, is also discussed as an option to adapt forests to global change (Jandl et al., 2019) in terms of cessation of management. Yet, its effectiveness is highly disputed, in particular regarding the time until forests have adapted to novel environmental conditions and can provide the desired ecosystem services (Puettmann & Bauhus, 2023). Assessments of unmanaged forests have shown higher reductions in tree growth in response to drought compared to managed stands (Herbst et al., 2015; Lucas-Borja et al., 2021).

While most previous studies rely on growth response indicators to assess the effectiveness of stand-based adaptation measures in relation to droughts (Schwarz et al., 2020), we focussed here on tree mortality, which is a more comparable and less context-dependent, ultimate indicator of drought resistance. Furthermore, we aimed to compile the information from single studies to draw general conclusion about the potential of the different adaptation options for European forests. For this purpose, we reviewed the published literature on the different topics and also contacted partners from within the RESONATE project as well as from other networks to assess the availability of additional, unpublished information. In milestone 4, we presented the potential data sources and in milestone 6 we evaluated their applicability to our study. Based on these, we decided to investigate the option thinning using a quantitative meta-analysis because there were sufficient publications and contributions of data sets from partners to follow this approach. The database for analysing the influence of tree species mixtures on drought mortality was not sufficient to adopt the same approach. Instead, we collected data on tree mortality in relation to tree diversity using the FunDivEurope platform, a network of forest research plots that spans over 6 different countries and forest types in Europe (Baeten et al., 2013). Here, we carried out a re-inventory of the plots to assess whether tree diversity reduced mortality following the recent severe pan European drought events. However, the analysis of these inventories is not yet finished. Thus, for the options mixed-species forests and unmanaged forests we relied on a review of the literature to give an overview of their potential to mitigate disturbances.

This deliverable provides an interim status of the task 2.4 “Silvicultural options to increase resilience”. In the course of the project, we will further investigate which barriers prevent forest owners and managers from implementing these mitigation options.

2. Potential of Thinning to mitigate drought-related tree mortality

2.1 Description of the evidence base

In MS 12 we reported on a solid base of publications on thinning, drought and mortality. There were even several existing studies at higher levels of evidence (after Binkley & Menyailo, 2005) including one meta-analysis and seven studies of at least national extent (Fig.3).

For our meta-analysis on the effect of thinning on drought-induced mortality, we searched in online publication databases, screened more than 1000 publications and selected those that reported quantitative data on thinning and mortality and incorporated at least one drought event. Subsequently, we compared the mortality in thinned and control treatments using the risk-ratio meta-analysis technique (Borenstein et al., 2009). The risk ratio describes the risk of an individual tree to die in a thinned treatment compared to the control and it is quantified as mortality rate in thinned stand divided by the mortality rate in the control stand. Usually, the risk ratio is below 1 following thinning, because thinning pre-empts competition-induced mortality by removing suppressed trees that are about to die, or thinning may also remove dominant or co-dominant trees and release suppressed trees (Monserud et al., 2004). As we were interested in the mortality rates induced by a drought that occurred additionally to the competition mortality, we investigated how the risk ratio changed from pre-drought conditions to periods after drought. Furthermore, we analysed moderators that could influence the relation between thinning, mortality and drought, such as age, climatic zone, species or time since last thinning. Lastly, we also assessed the canopy status of the trees that died before and after a drought period to see if the release of dominant or co-dominant trees through thinning could have adverse effects on these trees through increased exposure. To assess this, we used the dominance index which relates the proportion of the number of dead trees to the proportion of basal area of dead trees (Meyer et al., 2022). A dominance index higher than 1 indicates that dead trees were of below average size (suppressed) and conversely an index >1 would indicate that trees of above average dimensions (dominant and codominant) had died.

Our literature search and the contribution of partners led to a compilation of 36 experiments from 9 different studies that suited the requirements of our analysis (Willig et al. unpublished). Many studies, including some assessed in MS 12, needed to be discarded for the analysis because the reporting of data was insufficient for the standards of our meta-analysis.

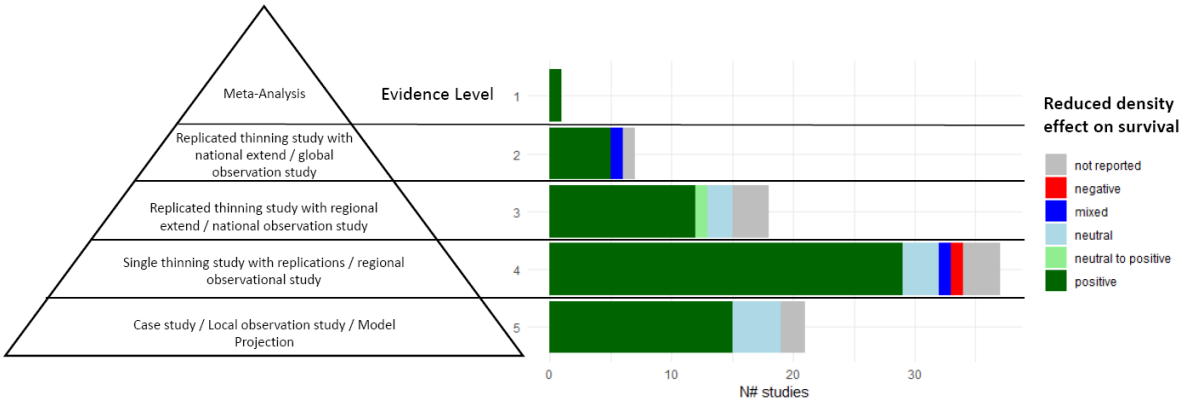

Figure 1 Evaluation of the quality of evidence base on thinning. Explanations of evidence levels see below, studies are counted in the bar chart on the right, green is indicating a positive effect, light-green a predominantly positive, light-blue a neutral, blue a mixed, red a negative and grey an effect that was not reported, the evidence pyramid is taken from Binkley and Menyailo (2005) and modified

2.2 Information on the potential of this measure

Our meta-analysis suggests that the change in mortality rate between thinned and control stands is not significantly different (Willig et al. unpublished). The risk ratio decreased from 0.329 before drought to 0.246 after drought, which means that when a stand was thinned, the risk to die for a tree was 67% lower before a drought and even 75% lower after drought

(Fig.1, bottom). So, it appeared that drought-related mortality was lower in thinned than in un-thinned stands, however this effect was not significant owing to the large variation. This large variation can be attributed on the one hand to the large standard errors that occur when very low or no mortality (one or zero dead trees) occurred in a period. On the other hand, the results from single studies differed unusually strongly from the common pooled result (Fig.1). We infer that these differences of experiments could at least partly be explained by moderators, such as tree age or time since intervention, of which we only found thinning intensity and climatic zone as weakly significant. Using a higher number of experiments for this kind of analysis could reveal if the observed trend of thinning to prevent drought-related mortality is relevant and how moderators influence this trend. Nevertheless, the analysis also showed that thinning clearly does, on average, not exacerbate tree mortality. Applying the dominance index on the experiments in our meta-analysis pool we could show that the dead trees were on average suppressed in thinned and unthinned treatments both before and after drought (Fig.2). Accordingly, thinning did not provoke a shift in drought-related mortality to more dominant trees.

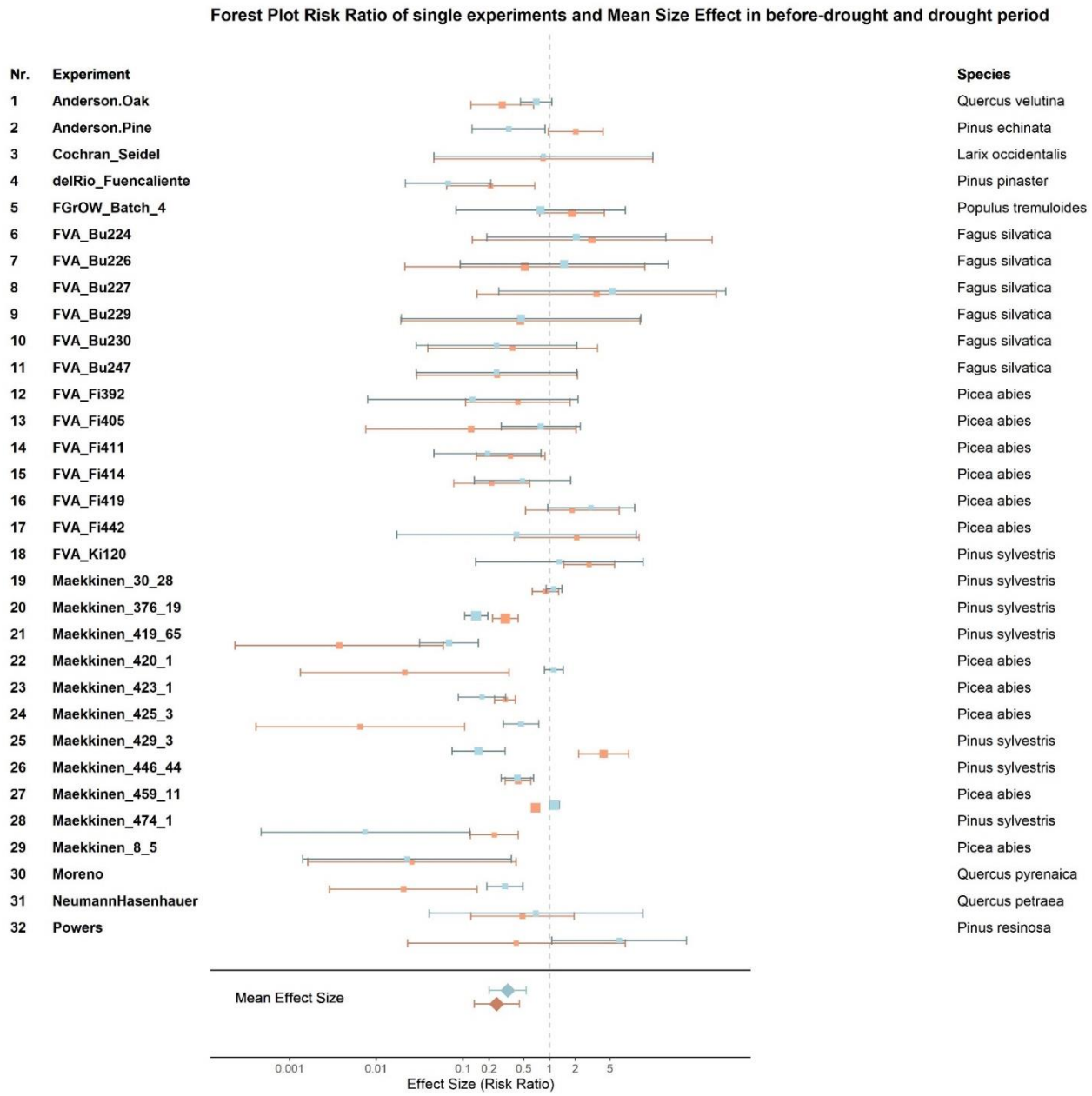

Figure 2 Forest plot of the meta-analysis on thinning effects on drought-related mortality (Willig et al. unpublished). Pre-drought period (blue) and drought period (orange) effect sizes are shown as risk ratio, x-axis is in log scale, size of square represents the weight, the lower the effect size the lower is the mortality rate in thinned stands relative to their control

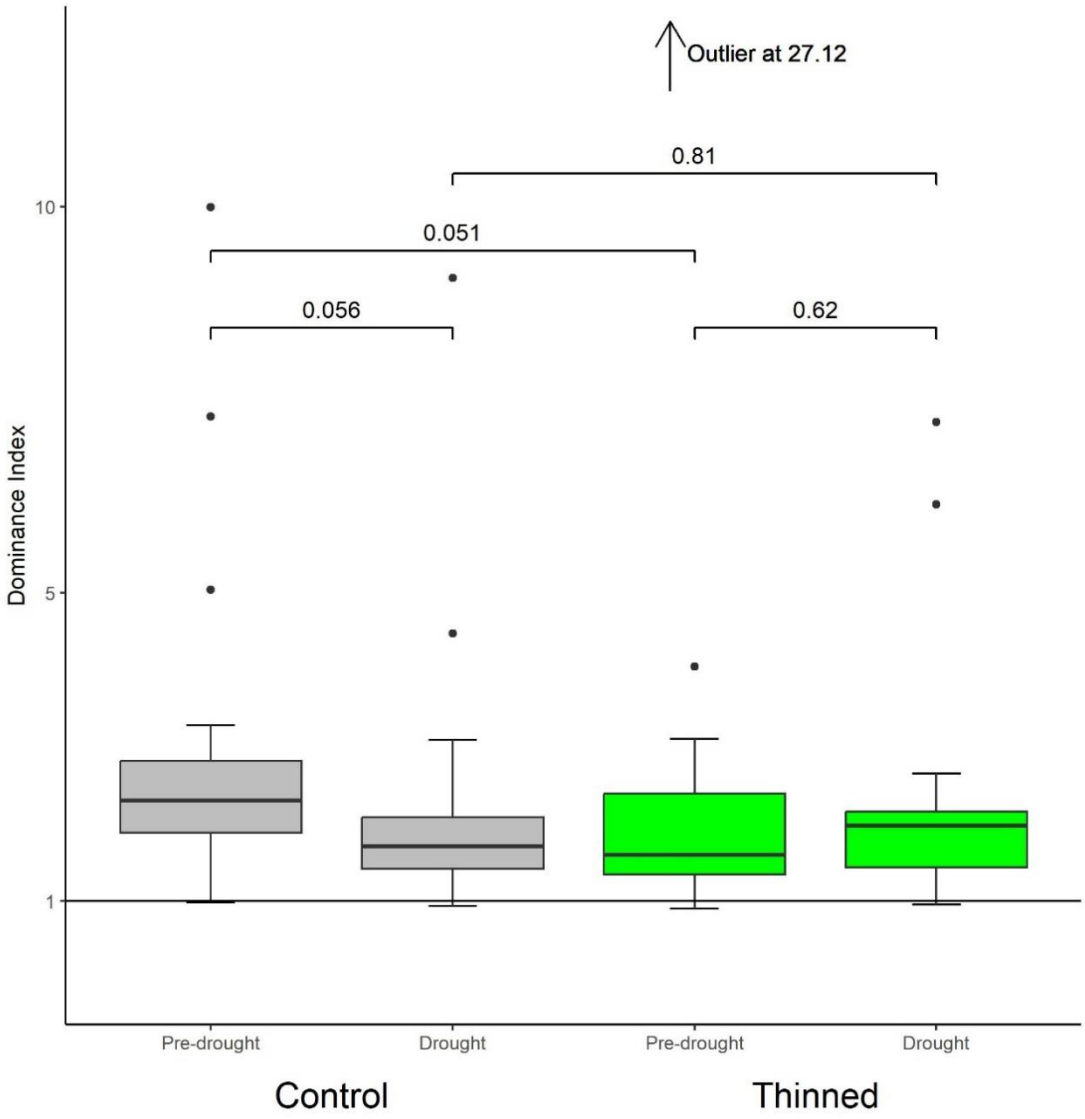

Figure 3 Boxplot on dominance of dead trees (Willig et al. unpublished). Dominance index of trees that died before and after drought in control (grey) and thinned (green) treatments, values above 1 indicate the convolute of trees that died had a lower dominance compared to the living stand, brackets with p-values indicated the significance of differences between groups tested with Wilcox-Test, there is an outlier in the thinned pre-drought group at 27.12 that is not shown in the graph

2.3 Conclusion

Based on our meta-analysis, we could not provide robust evidence that thinning reduces drought-related tree mortality. We found a large variation in effect sizes (risk ratios) between the single experiments. This corresponds with other meta-analyses that assessed the effect of thinning on drought response of radial growth and hydraulic processes (Castagneri et al., 2021; del Campo et al., 2022; Sohn et al., 2016), indicating that differences between experimental sites and thinning regimes alter the effectiveness of thinning to reduce drought stress substantially. In the literature, the identity or taxonomic class of the respective species (Bottero et al., 2021; Sohn et al., 2016), the quality of site (Gleason et al., 2017) and the intensity of thinning (del Campo et al., 2022; Gebhardt et al., 2014) were characterised as important factors influencing the thinning effectiveness. In our analysis, the latter two were contributing weakly in explaining the differences of effect sizes between experiments. Nevertheless, we demonstrated that mortality does not increase in thinned stands after drought, especially not in bigger trees. This finding contradicts assumption that the release of trees with larger crowns could lead to a higher risk of mortality as the sudden radiation followed by increased transpiration overwhelms the hydraulic system of tall trees (Jump et al., 2017; Stovall et al., 2019). Our results of the risk ratio and dominance index analysis underline that other potential advantages of thinning concerning resilience of forests, such as the shortening of production times, the possibility to introduce advanced regeneration or the better recovery of tree growth following drought, are not impaired by higher mortality.

3. Potential of mixed-species stands to mitigate drought-related mortality and other disturbances

3.1 Description of the evidence base

The number of studies that considered the influence of tree diversity in mixed-species forests on drought-related mortality is very sparse. For that reason, we switched from searching strictly for drought-related mortality to searching for resilience to drought (in terms of tree mortality, tree growth or hydraulic variables). Still, there are much more publications that address the relationship between tree diversity and productivity than the influence of tree diversity on resilience (e.g. as response to drought). Already in our assessment of demonstration sites for our management options in MS 4, we could not find any experiments for mixing species stands that also assessed mortality in our projects case study areas. To address this deficiency, we analysed drought-related mortality in a network of plots with different tree diversity of the FunDivEurope-Project, however, this analysis has not been completed yet. For this report, we assessed the potential of mixing tree species for enhancing resilience to drought from the studies that we identified in MS 12 (Fig.4). In total, 20 of 38 studies showed positive and predominantly positive effects of tree diversity on resilience to drought. We found no meta-analysis but eight studies on the second best evidence level (reviews and studies of at least national extent) that were analysed in more detail for this report. We also considered studies of similar evidence quality that were provided by partners in the stakeholder meeting and the project meeting, both in September 2023.

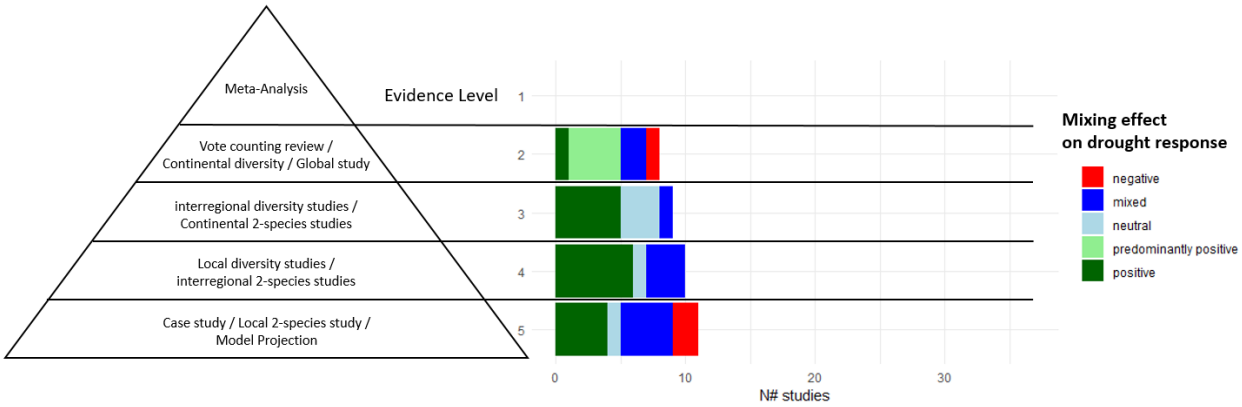

Figure 4 Evaluation of the quality of evidence base on mixed forests. Explanations of evidence levels see below, studies are counted in the bar chart on the right, green is indicating a positive effect, light-green a predominantly positive, light-blue a neutral, blue a mixed, red a negative and grey an effect that was not reported, the evidence pyramid is taken from Binkley and Menyailo (2005) and modified

3.2 Information on the potential of this measure

Table 1 Description of the findings of selected publications on tree diversity / mixed forests effects on disturbance response, in the last column it is discussed if an effect is driven by the identity of species within the composition or the richness of species per se

Reference	Type of publication	Main findings	Species identity vs species richness
Ammer 2019	Review	The review concerns mainly the relationship between tree diversity and productivity, but it includes physiological explanations and findings that explain reactions to drought in mixed forests. Drought reactions are variable because they depend on site characteristics in combination with species identity. Both characteristics are decisive for the question whether positive complementarity effects are supported by drought or if selection effects take over with less clear consequence for mixture effects. Generally, stability of more divers forests seems greater, because some species appear to be less stressed in mixtures. However, mixtures that are very productive also have higher transpiration rate which could accelerate the development of soil drought situations.	The identity of the species in mixture seems to be more important than species richness in mixture.
Anderegg et al. 2018	Global study	The study summarized the data of eddy covariance flux tower sites in forest globally. The authors investigated the effect of physiological plant traits related to water transport on forest ecosystem response to drought. Forests with a greater diversity in those traits (especially with diverse hydraulic safety margins) buffered transpiration during droughts better (measured as latent energy exchange).	The traits are species-specific, however a number of species is important to achieve a diversity here.

Diaci et al. 2017	Review	The review concerns forest restoration after disturbance in mixed, uneven-aged (close to nature managed) forests. It states that through gradual release, the individual trees are more resistant (h/d-ratio, crown/root architecture). However, it mainly discusses the advantages of more structure on disturbance recovery on different size gaps. Advanced regeneration and enhanced microsites are the main reasons for better recovery.	The focus is more on structural diversity here, species-specific properties are not addressed.
Grossiord, 2020	Review	The review of 28 studies that measured forest response to drought in relation to forest diversity could detect an effect between diversity and response. Interestingly, the effect was not strictly unidirectional, but still predominantly positive. Forest response seems very context-dependent, namely abiotic and biotic environment, management and species composition are important (direction of effect can change with drought conditions). Also, the target variable response was measured differently (in terms of growth, hydraulics, etc., and on different scales) which lead to contradictory results and is difficult to interpret. Underlying mechanisms could not be assessed (lack of trait information).	Neither could be completely addressed, few studies that had more than 3 species, but also the lack of trait information exacerbate species diversity and identity investigations.
Grossman et al. 2018	Review	This review summarized the results of studies within the TreeDivNet platform (https://treedivnet.ugent.be/). The authors focused on survival and growth (but without a specific disturbance) and herbivory and pathogens. Overall they could find neutral or positive effects of diversity on survival and growth. Some studies could definitely carve out complementarity effects. Regarding functional traits, it seems that a higher community weighted mean is more decisive than a higher trait diversity for overyielding in mixtures. There were all kinds of effects (0,+,-) of diversity on herbivory or pathogens. They seem to rely on tree size, phylogenetic diversity and spatial arrangement. As forests are young in TreeDivNet experiments, it was difficult to see diversity effects on predators of herbivores.	Both species identity and diversity was stated as important for diversity effect differing from case to case (and target variable).
Haberstroh & Werner 2022	Review	The review of 18 studies assessed hydraulic variables measuring water stress and the effect of mixtures on those. In mild droughts positive mixture effects prevailed due to complementarity (above- and belowground) as well as hydraulic lift. In severe droughts results are less clear, with often one species becoming more competitive in water usage while the other (mostly conifers here) perform worse than in monoculture. Performance is worse for both species when increased competition instead of complementarity dominates the mixture effect in extreme droughts. Recovery was less studied, however it seems that mixtures could have	The authors hint that other species combinations could show net positive mixture effects even under severe droughts. Tree species richness is not specifically addressed.

		longer recovery times under severe droughts. Species that have reduced resistance, benefit from mixtures during recovery. Sometimes dominant species become more dominant and prolong recovery of the other species or they become less dominant and competition on the other species is released.	
Jactel et al. 2017	Review	The review investigates the effect of tree diversity on resistance to disturbances in general. The influence of tree diversity on drought is unclear because the severity of drought impacts on individual trees depends strongly on site characteristics and species composition. It seems that effects of tree diversity are rather positive at good sites (tropical and temperate biomes), whereas it might be neutral at harsher sites (Mediterranean, mountains) and negative in boreal sites. Possibly water efficiency is enhanced in mixtures which however conflicts with the theory that more productive forests also use more resources. For other disturbances we see mixed effects (fire), mixed to positive effects (mammal and insect herbivory) and mostly positive effects (pathogens, wind) of tree diversity.	The response of mixed forests to drought is often asymmetrical (one species wins, the other loses). It is not yet fully understood how the asymmetry works and thus which properties should be combined to get a feasible species mixture.
O'Hara & Ramage 2013	Review	The review on multi-aged stands and disturbance resistance and resilience advocates for the potential of more structural complexity in future forestry. Multi-aged forests are often intertwined with mixed forests. They offer more resistance due to a broader range of structures (selection effect). Resilience is enhanced by the structures that remain after disturbance, either younger more plastic trees that fill gaps or by the capacity of old trees to serve as seed trees.	Here mainly the selection effect is the key. More diversity means more complexity which fosters risk spreading.
Ratcliffe et al. 2017	Continental study	In this study, the species richness effect on ecosystem functions in the FunDivEurope network was assessed. Generally, species richness has positive effects on all functions, but is very context-dependent. For resistance-related ecosystem functions (EFs), the context-dependency is even higher compared to other EFs. Resistance-related EFs were enhanced by species richness in water-limited sites in Southern Europe, whereas the effect was neutral or negative in Finland, where water availability was high. In Central Europe, where water availability was moderate, the effect was more positive the longer the vegetation period and the higher the functional diversity was.	It is mentioned that the impact of diversity and identity of species is comparable over all EFs. However, it seems that for resistance EFs identity is a bit more relevant.
Searle et al. 2022	Continental study	In this inventory-based study, the effect of tree diversity on mortality in North-American forests was investigated. Mortality clearly increased with increasing tree diversity. Diversity is the third best predictor of mortality behind tree size and age in temperate forests (5th in boreal). The authors	Only diversity is regarded here.

		explain the higher mortality with higher productivity leading to higher stand basal area and more competition in mixtures. The study assessed mortality in general (not specifically related to a disturbance) in unmanaged forests.	

3.3 Conclusions

The investigated reviews and studies concern different aspects of tree diversity, sometimes rather structural complexity, and mainly resistance and partly resilience to disturbance, which can be measured in different ways (more on that later in section 5). A commonality is that they try to capture tree diversity effects that describe how a mixed tree community behaves different from a monoculture (or less divers forest). The mechanisms behind the diversity effect are complementarity, facilitation and selection (Ammer, 2019; Grossiord, 2020; Grossman et al., 2018). While the first two mechanisms are rarely separated, it is often sought to differentiate between complementarity, the mechanism describing how the interplay of tree species changes resource efficiency (e.g. root stratification) and selection, meaning that the diversity effect can be traced to certain species that do better or worse in mixtures.

Considering drought as a disturbance, the reviewed papers suggested a mixed to positive effects of tree diversity on drought resistance. It is important to note that the reaction was context-dependent throughout almost all papers and single negative reactions were also possible. Site characteristics (abiotic and biotic environment), management as well as species composition were mentioned to be decisive for the effect in several studies. However, for site characteristics it is not quite clear how they work. It has been found that positive effects of mixing were greater on drier sites (Jactel et al., 2017; Ratcliffe et al., 2017), whereas one other study showed that the effect turns negative when a drought gets extreme (Haberstroh & Werner, 2022). Several reviews have shown that divers forests are more productive (Ammer, 2019; Forrester & Bauhus, 2016), which not necessarily translate in higher resistance or resilience. Contrary, there is the theory that more diverse forests are more productive, have a greater water consumption and thus could be especially at risk in drought situations. Unrelated to drought, there was the finding that increased productivity in mixed forests leads to more competition and higher mortality in unmanaged forests (Searle et al., 2022). This also shows that the negative effect could be regulated by stand density management. Lastly, the species composition turned out to be quite relevant, in many cases more relevant than the species richness. Papers that concerned functional traits explained that a higher dissimilarity in water-related traits could enable complementarity processes (Ammer, 2019; Anderegg et al., 2018; Haberstroh & Werner, 2022). Also, selection processes can be driven by specific species. As there are often asymmetric responses to drought (one species does better than another), the reaction of the whole stand depends on the identity of tree species. Correspondingly, in terms of functional traits a greater importance of trait mean values, that are driven by the dominant species, compared to trait diversity values, which are driven by higher species diversity (Grossman et al., 2018).

The papers that concerned other disturbances than drought also described species identity in many cases to be more important than species richness, especially for mammal and insect herbivory as well as pathogens that are often host-specific. These three disturbances had advantages and disadvantages of increased tree diversity that often went hand-in-hand, for example it could be more difficult for specialists to find the specific host tree while generalists benefit from more from a variety in diet. In the end, the effect of tree diversity was on average more beneficial, probably because generalists are not as impaired in

monocultures as specialists are in mixed forests. In contrast to fire, for which a negative effect of diversity has been observed, diversity had mostly positive impacts on wind as disturbance. Both is probably closely connected to the enhanced structures that comes with mixing. Two papers that were rather focused on structurally complex forests also found that the remaining structures after a disturbance lead to better recovery and thus resilience in total (Diaci et al., 2017; O'Hara & Ramage, 2013). Most important here is advance regeneration that could establish in structurally divers forests, survived the disturbance and gave better conditions for the next stand to form. Additionally, structurally diverse forests are more resistant to some disturbance that affect only trees in certain sizes, e.g. bark beetles, due to selection processes (other size classes are not affected or even benefit). With small scale management, typical for structurally diverse forests, trees are gradually released and can gain more individual fitness and resistance to disturbances (Diaci et al., 2017).

4. Potential of cessation of active forest management to mitigate drought-related mortality and other disturbances

4.1 Description of the evidence base

For the option cessation of active forest management, the evidence base was even lower compared to the other management options (Fig. 5). We could not find many studies that concerned the effect of droughts in managed and unmanaged forests, therefore we broadened the scope in MS12 and looked at disturbance mortality in general. In MS 12, the effect of management on mortality was unclear, 14 of 30 studies reported positive and predominantly positive results while the rest of the studies reported mixed or negatives results. Here we assessed the potential of mitigating disturbance impacts again with selected studies from MS12 and input that was provided from stakeholders and partners at the stakeholder and project meeting in September 2023. The level of evidence is also much lower as we could report mostly only from individual local studies, but not from large-scale studies or reviews.

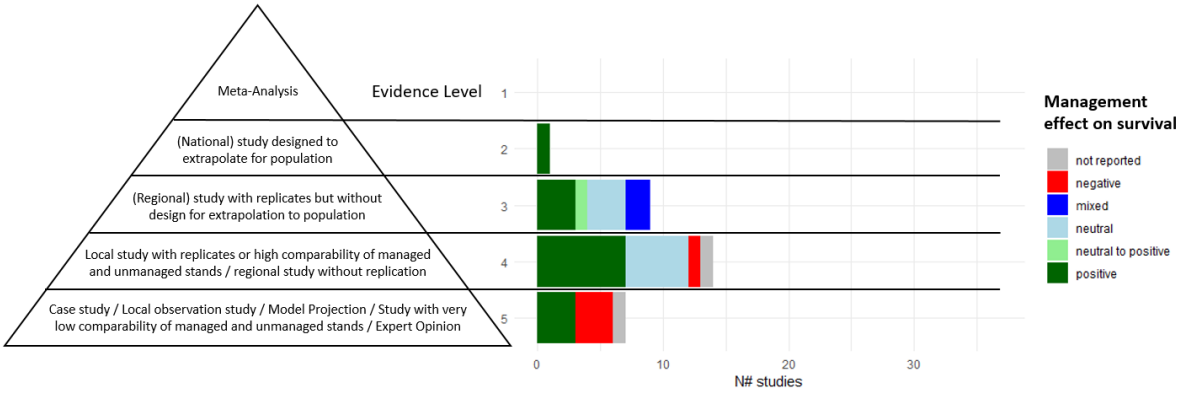

Figure 5 Evaluation of the quality of evidence base on unmanaged forests. Explanations of evidence levels see below, studies are counted in the bar chart on the right, green is indicating a positive effect, light-green a predominantly positive, light-blue a neutral, blue a mixed, red a negative and grey an effect that was not reported, the evidence pyramid is taken from Binkley and Menyailo (2005) and modified

4.2 Information on the potential of this measure

Table 2 Description of the findings of selected publications on management effects on disturbance response

Reference	Type of publication	Main findings
Gleason et al. 2017	Thinning study, comparison of managed and unmanaged plots	The study compiled thinning experiments across an aridity and forest type gradient in the northeastern US. Higher tree density in unmanaged control stands exacerbated growth decline in droughts. The effect was ubiquitous but increased from dry to humid sites. The authors suggest that trees in better conditions can make more use of the available resources after thinning while trees in dry sites may have less acquisitive strategies.
Guillemette et al. 2017	Retention forestry, comparison of managed and unmanaged plots	The study investigated the mortality in partially cut and unmanaged forests from a broad plot network in Quebec. Partial cuts reduced the mortality per area but the mortality rate (per N) stayed the same. Harvesting in more vigorous tree classes reduced the mortality from insects and diseases.
Herbst et al. 2015	Eddy covariance measurements, comparison of managed and unmanaged plots	The study compared the results of two sites with eddy covariance towers, one managed, the other not. Evapotranspiration was higher in unmanaged stands, potentially due to higher LAI leading to higher interception or transpiration. Net carbon uptake was more strongly reduced in unmanaged forests in the drought year 2003. The authors attribute it partly to the occurrence of ash in the unmanaged stands, as it has a weaker performance in late summer droughts.

Kara 2022	Dendroecological study, comparison of managed and unmanaged plots	In this study, the author investigates resilience to drought in managed and unmanaged forests with the help of tree cores taken from firs in northern Turkey. Tree growth reduction during drought was smaller in managed forests compared to unmanaged forests, suggesting a lower drought resistance of unmanaged forests. The authors assume that the structural complexity that was actually greater in managed forests also contributed to greater drought resistance.
Klockow et al. 2020	Inventory study, comparison of managed and rather unmanaged plots	The study assesses mortality after drought in managed and mostly unmanaged plots in Eastern Texas. Mortality after an exceptional drought was lower in managed stands compared to unmanaged stands. The authors attribute it to the greater competition due to greater stem density in unmanaged stands.
Lucas-Borja et al. 2021	Dendroecological study, comparison of managed and unmanaged plots	The study compared radial tree growth in managed (as shelterwood) and unmanaged black pine plots located in Central-Eastern Spain. Trees in managed stands were more drought resistant. The authors attribute the greater growth reduction in unmanaged stands to greater competition for water.
Meyer et al. 2022	Study on mortality in strict reserves and adjacent managed stands	The study took place in strict reserves and adjacent managed reference stands of Beech in Hesse and was measuring mortality after extreme drought event 2018-2019. There was enhanced mortality in the reserves after drought whereas the rate did not significantly change in managed forests. However, in managed stands mortality shifted to a small degree to larger canopy trees during drought.
Roberts et al. 2020	Review on management effects on pathogens	This review assessed different management options and their effect on the spread of pathogens. Changes in canopy were positive or negative depending on whether the respective pathogen preferred humid or dry air. Controlling tree mixtures and density could contribute to avoiding infections. Negative effects of management are the higher risk of incidence through stumps or injuries that followed cuttings. The spread of pathogens could be delayed by removing infected trees but not stopped.
Stritih et al. 2021	Study on disturbances with satellite and historical data	In this study that took place in Graubünden (CH), the authors identified disturbances with satellite and historical data and estimated which factors contribute how much to disturbance susceptibility of forests. They found that secondary forests that were planted after 1920 were more susceptible compared to older forests. However, the older forests were typically managed, whereas in secondary forests only sanitation cuts were conducted. The authors assume that

		heterogeneity was promoted in older managed forests, which is the reason that they were less susceptible compared to more homogenous secondary forests (often spruce). Lastly, they showed that recent management (within last 10 years) clearly increased disturbance susceptibility.
Ward et al. 2022	Study on mortality after *Lymantria dispar* occurrence	The study took place in southern New England, US. The authors assessed mortality in experimental forests before and after outbreaks of *Lymantria dispar*. They could not detect a difference in mortality between managed and unmanaged forests. They stated that there is a mixed effect of management on infection of trees reported in literature.

4.3 Conclusions

We found some studies that reported research in unmanaged forests and comparable reference areas, however the research was concerning static variables such as structure, and did not take into account dynamics, such as the response to disturbances (e.g. Adamic et al., 2017; Čavlović et al., 2021). We conclude that a lack of managed reference plots to unmanaged plots, but also suitable long-term study designs are restricting the evidence base.

A big share of the reviewed studies state that unmanaged forests are more vulnerable to disturbances because they suffer from greater competition. When drought is the studied disturbance, reduced water availability due to competition directly affects the trees, and their lowered fitness due to competition might make them more vulnerable to insect and pathogen attacks. It is noteworthy that the forests researched in the reviewed studies were not old-growth forests, they have received in the past some form of forest management until a certain point in which management stopped. Accordingly, they do not necessarily exhibit greater species or structural diversity, e.g. in the case of Stritih et al. (2021) and Kara (2022) the latter was lower. We see that this is line with our study question because the cessation of management as management option would mean that the respective forests were managed before. Restarting management in these homogenous forests that have been untended for a while bare the risk of disturbance damage immediately after the intervention (Stritih et al., 2021). Generally, we believe that cessation of management hinders adaptation of forests that consist of species that are not site-adapted and/or have been very simplified for production purposes, for example lowland spruce forest in Central Europe. For forests that match the current environmental conditions better, the question is less clear, for example older Beech forests in Central Europe (Jandl et al., 2019; Meyer et al., 2022).

5. Insights on the overall potential of stand-level forest management measures to mitigate disturbances

In our assessment of the effectiveness of management options, we mostly addressed resistance (as part of the engineering definition of resilience (Nikinmaa et al., 2020)) of existing forest stands. Still, this measure can be unclear, for example regarding drought it can be measured with hydraulic variables, mortality or growth response, of which none is more correct than the other and they do not necessarily have to point in the same direction (Grossiord, 2020). Here, we tried to describe the results (in section 3 and 4) in order to relate the context of the studies to the study question in a comprehensive way. Further we included

few studies that addressed resilience as the ability of the forest system to bounce back after disturbance, for example through advance regeneration (see Nikinmaa et al., 2020). What we can see from the studies considered here is that we rarely find publications that addressed the effects of several disturbances in parallel Moreover, the selected studies rarely incorporated variables that characterize the response of whole tree communities to disturbances respectively their return to pre-disturbance states, but rather used variables of individual trees (e.g. tree rings) to characterize resistance and resilience.

For thinning, we concluded that there appears to be a beneficial effect on mortality after drought, but this is not significant. However thinning had on average no adverse effect on mortality and thus can be recommended for the other positive effects (Moreau et al., 2022). Specifically, the recovery of tree growth after drought (Sohn et al., 2016) and the potential to establish advanced regeneration (Millar et al., 2007) are to mention. Correspondingly, we can also advocate to promote mixing tree species even though a universal positive effect was not found. Generally, the effect was mixed to positive depending on the site context for all disturbances except fire. In fire-prone forest one should put more emphasis on managing forest structure than diversity. The portfolio effect, meaning having more species in the stand for the case that one species fails, might become even more important as the future of biotic (and also abiotic) disturbances is uncertain. The disadvantage of greater resource use due to more productivity in mixed forests could be mitigated with thinning. The main reason for cessation of management should be conserving biodiversity. There is no hint that unmanaged forests could adapt better to global change. Nevertheless, the passive adaptation dynamics of unmanaged forests could provide valuable information for forest management. Accordingly, the monitoring should be promoted and standardized to achieve a greater evidence base in this field. Research on the dynamics and responses to disturbances in primary forests (like in the Remote primary forests project, https://www.remoteforests.org/) is helpful to understand long-term pathways of unmanaged forests. It should be supplemented with research initiatives (like the Euforia project, https://www.wsl.ch/de/projekte/euforia/) that also take into account more recently set aside forests from nature reserves or those that will be set aside with the implementation of the EU-Biodiversity-Strategy. Also, for the other two management options “thinning” and “mixed species stands”, coordinated monitoring and research would be essential to explain the large variability of their effectiveness in preventing drought stress that we found between and within studies. Exploring how the effect of management is influenced by tree species, stand density and site characteristics, of which the soil water holding capacity might be most important, would be helpful to create more specific adaptation management recommendations.

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