Willig *et al. Annals of Forest Science* (2025) 82:6
https://doi.org/10.1186/s13595-025-01278-7

Annals of Forest Science

REVIEW PAPER

Open Access

No increased drought-related mortality after thinning: a meta-analysis

Julius Willig[1*], Julia Schwarz[2], Philip Comeau[3], Henrik Hartmann[4,5], Ulrich Kohnle[6], Josep Maria Espelta[7,8], Harri Mäkinen[9], Roma Ogaya[7,10], Mikko Peltoniemi[9], Josep Penuelas[7,10], Brian Roth[11], Ricardo Ruiz-Peinado[12], Florian Ruge[6] and Jürgen Bauhus[1]

Abstract

Context Forest scientists are challenged to identify and propose evidence-based silvicultural options to mitigate the impacts of drought events induced by climate change. For example, it has been suggested that thinning increases soil water availability for individual trees by reducing stand density and stand-level transpiration. Many studies have assessed the impact of thinning on stem growth and transpiration of individual trees during and after drought events. Often, growth increases were observed, but not consistently, and their impact on tree survival following drought has rarely been addressed.

Aims We aimed to assess the effect of thinning on tree mortality, the ultimate indicator of tree resistance to soil water deficit induced by drought, with a focus on dominant trees.

Methods We conducted a risk ratio meta-analysis on tree mortality before and after an extreme drought event with 32 thinning experiments from nine studies in Europe and North America.

Results We showed that thinning reduced the overall mortality risk of trees. However, the lower mortality rate in thinned stands relative to unthinned stands in pre-drought periods was not further reduced during and after extreme drought events ($p > 0.05$). This may be due to the large heterogeneity and inconsistent reporting of mortality across the studies included in our analysis. Thinning did not exacerbate mortality among dominant trees.

Conclusion Since thinning did not increase mortality, its application can still be recommended for many other management objectives such as maintaining tree species richness or lower disturbance risks from windthrow. We propose better documentation of thinning trials to improve the data base for systematic reviews.

Key message

Our meta-analysis showed that thinning of forest stands did not increase mortality following extreme drought events. There was also no higher mortality among dominant trees that are typically more exposed to irradiance after thinning. We show that many thinning experiments lack sufficient documentation of mortality and climatic variation and urge for more comprehensive reporting to facilitate systematic reviews.

Handling editor: John M. Lhotka

*Correspondence:
Julius Willig
jwillig.forst@posteo.de
Full list of author information is available at the end of the article

Keywords Drought resistance, Climate adaptation, Silvicultural options, Dominant trees, Risk-ratio meta-analysis

1 Introduction

Drought and heat waves induced by climate change have accelerated forest mortality globally (Allen et al. 2010; Anderegg et al. 2013; Hammond et al. 2022; Hartmann et al. 2022; Neumann et al. 2017; Senf et al. 2020). For instance, in Europe forest mortality has increased continuously over the last 30 years (George et al. 2022; Senf et al. 2018; Spiecker & Kahle 2023), and there have been occurrences of large-scale mortality events such as the one triggered by the 2018–2020 drought episode (Schuldt et al. 2020). Mortality-accelerating drought events are projected to intensify, increase in frequency and become more widespread (Allen et al. 2015). The potential impact of these events calls for a better understanding of mortality processes (Hartmann et al. 2018; Klein 2020) and their consequences to forest management. Not only climate change mitigation goals, but also the provision of other important ecosystem services is and will be hampered by increasing tree and forest dieback (Anderegg et al. 2013; Cantarello et al. 2017; Hammond et al. 2022; Neumann et al. 2017; Seidl et al. 2016; Senf et al. 2020). An important strategy to counteract this development is to pro-actively manage forests for resilience and adaptive capacity (Himes et al. 2023; Lindner et al. 2020). Correspondingly, forest scientists are proposing actions for adaptation (Millar et al. 2007; Swanston et al. 2016) and are seeking to provide evidence for their effectiveness to inform management (Bauhus et al. 2021; Bolte et al. 2009; Lindner et al. 2014).

One possible adaptation strategy to increase the resistance and resilience of forest stands to drought is thinning (Himes et al. 2023; Ogaya et al. 2020; Sohn et al. 2016). Several studies have indicated that reducing stand density lowers stand-level transpiration and interception losses, at least until the crowns of the remaining trees have closed the canopy gap. Hence the lower transpiration results in more available soil water at stand level and for individual trees (Breda et al., 1995; Cotillas et al. 2009; del Campo et al. 2022). Accordingly, trees in thinned stands may have longer access to water during shorter drought periods compared to those in denser, unthinned stands (Breda et al., 1995). In extreme and long-term droughts, however, soil water is usually depleted in thinned stands as well. Even in the latter situation, thinning may improve the response of trees to drought through faster recovery of root systems (Lopez et al. 1998) and reduced competition for light and nutrients (Sohn et al. 2016) following drought events.

Two meta-analyses (Castagneri et al. 2021; Sohn et al. 2016) reported that thinning commonly mitigates tree growth reductions during or after a drought event. However, the benefits of thinning found in the studies were context-specific, for example, influenced by factors such as tree species, tree age, time since last intervention and site aridity. In contrast, negative impacts on growth response to drought were observed in a thinning experiment with *Picea abies* Karst. in Bavaria for a heavy thinning from above aimed at releasing future crop trees (Hilmers et al. 2022).

While there have been many individual studies and some quantitative reviews on the growth responses of trees to drought (Bottero et al. 2017; Castagneri et al. 2021; Hilmers et al. 2022; Sohn et al. 2016; Steckel et al. 2020), few studies addressed most important question related to drought stress: whether thinning reduces or increases tree mortality in case of severe drought events, or may have no effect. A recent literature review on thinning effects on disturbance-related growth declines and mortality found evidence for decreased tree mortality following drought in thinned stands (Moreau et al. 2022). However, this review lacked a quantitative analysis (e.g. meta-analysis) which would clarify to what extent mortality is reduced and how thinning effects depend on experimental design and site conditions. Thinning effects mitigating mortality of *Pinus halepensis* Mill. in Israel increased with the intensity of thinning treatments (Calev et al. 2016). This was explained by substantially higher soil water availability, measured through pre-dawn leaf water potential. Similarly, the reduction of persistently high mortality rates in *Pinus sylvestris* L. forests in Switzerland was due to the release of drought stress, as indicated by higher leaf area to sapwood area ratios in trees in thinned stands (Giuggiola et al. 2013). A study that used national forest inventory data for the Western USA found that reducing basal area was particularly effective in preventing forest mortality in *Pinus ponderosa* Douglas ex. Loudon forests in areas that experience high temperatures or multiyear droughts (Bradford et al. 2021). Similar results were observed in mixed conifer forests in California, where lower mortality in thinned stands was attributed partially to less severe bark beetle infestations following a drought (Knapp et al. 2021). The authors assumed trees in thinned stands were more vigorous and thus had better defence against bark beetles from greater resin exudation (Knapp et al. 2021). The comparison of unmanaged and managed *Fagus sylvatica* L. forests in Hesse (Meyer et al. 2022) and Baden-Württemberg

(Bucher et al. 2023) revealed no general influence of management (mainly thinning and single tree selection) on mortality after drought but a slight shift of mortality in managed stands towards more dominant trees.

To clarify if these observed effects of thinning on tree mortality display a consistent pattern across Mediterranean, temperate and boreal forest types worldwide, we conducted a meta-analysis based on data from thinning experiments. Owing to the limited availability of suitable studies, our analysis was restricted to thinning experiments in Europe and North America.

At the single tree level, large and exposed crowns amplify the water demand compared to smaller crowns, which can lead to higher transpiration stress in drought situations (Bennett et al. 2015; Stovall et al. 2019). Thinning may exacerbate this stress since it increases the exposure of tall and dominant trees to incident radiation. In addition, increased wind movement in the canopy can lead to greater transpiration rates through disturbing the boundary layer around the foliage. To account for the potential mortality after exposure and to determine whether the observed shift in mortality towards dominant trees, as reported by Meyer et al. (2022), can be generalised, the Dominance Index (DI, Meyer et al. 2022) which relates the frequency-based proportion of trees that died to their basal area-based proportion appears particularly useful.

We addressed the following hypotheses in this study:

1. Drought-related mortality is lower in thinned versus unthinned stands.
2. In thinned stands, mortality shifts from suppressed to larger, dominant and more exposed trees.

Studies on thinning effects on drought-related mortality were predominantly located in regions with a history of frequent drought events (Bradford et al. 2021; Calev et al. 2016; Giuggiola et al. 2013; Knapp et al. 2021). Several investigations document that thinning was more effective in preventing drought-related growth declines on dry sites (Schmitt et al. 2020; Steckel et al. 2020); while others have demonstrated benefits of thinning associated with increasing soil moisture (Gleason et al. 2017). We, therefore, also examined through meta-regression analysis, if there is an influence of the general climate at the experimental sites on the effectiveness of thinning in reducing drought-related mortality.

Since Sohn et al. (2016) and Bottero et al. (2021) observed differences in radial growth response to drought in conifers and broadleaved trees, we also considered taxonomic class as a factor in our analyses, along with tree age (Lucas-Borja et al. 2021; Steckel et al. 2020) and time since the last thinning (D'Amato et al. 2013; Sohn et al. 2016).

Previous studies on drought-related mortality have identified lag effects, where several years may pass before mortality is observed following a drought (Trugman et al. 2018; Bigler et al. 2007). For example, trees die post-drought when they cannot acquire enough carbon to repair damaged vessels (Trugman et al. 2018). To capture lagged tree mortality, we examined the differences between treatments both in the period immediately after the drought event and the subsequent period.

In summary, the aims of this meta-analysis were to assess (a) whether thinning is a suitable forest adaptation option to mitigate mortality after droughts, (b) whether thinning influences which trees are more likely to die following drought events, and (c) which covariates, such as thinning method or intensity, drought intensity, stand structure characteristics or site conditions, determine whether thinning effects reduce or increase tree mortality.

2 Material and methods

2.1 Literature and data search

We conducted a detailed literature review of studies that reported mortality in forest thinning experiments using the online databases, Web of Science© and Elicit©. We contacted research institutions and investigators who had previously published studies on thinning experiments, requesting unpublished data to include in the meta-analysis. To collect all relevant publications and contributions, we queried Web of Science© with search terms in the four categories "forest", "management", "mortality", "drought" and one for the exclusion of misleading topics (Appendix Table 3). This search yielded 813 potentially relevant studies. We used Elicit (Elicit 2022) and entered the search question "How does forest thinning affect drought-induced mortality". From the returned literature suggestions, we retrieved the first 160 suggested articles; the remaining articles were only marginally relevant for the purpose of our study. Four colleagues provided unpublished datasets of thinning experiments and two more colleagues provided additional material to complement their publications (Table 1). During this process, we identified another 82 relevant articles from the citations and added them to the pool. Altogether, 1032 studies formed the first pool.

After compiling all studies, we identified studies that (1) were conducted under field conditions; (2) included at least one thinning treatment and an unthinned control; (3) quantified tree mortality (expressed as number of trees or stem basal area per hectare); and (4) reported drought-related mortality events that were not

Table 1 Overview of experiments included in the meta-analysis. The column Publication/contribution states the source, which is either a publication or a contribution of a partner. Tree Age refers to the stand age at the beginning of the pre-drought inventory period. $SPEI3_{Summer}$ is the SPEI of the 3 summer months (June, July, August or December, January, and February) of the drought year stated in the previous column. Time since the last thinning is given in years and counted until the start of the pre-drought inventory period. Plot areas are given in hectares

Nr	Experiment	Publication/ contribution	Region/ country	Koeppen climate zone	Tree age	Pre-drought inventory period	Drought inventory period	Drought year	$SPEI3_{Summer}$	Ratio SDI thinning vs control	Time since the last thinning	Main species	Latitude	Longitude	Plot area control	Plot area thinning
1	Anderson-Oak	Anderson (2017)	USA—Missouri	Dfa	79	2001–2009 (8)	2009–2015 (6)	2012	−2.40	0.68	35	*Quercus velutina* Lam	37.5	−91.25	0.2	0.6
2	Anderson-Pine	Anderson (2017)	USA—Missouri	Dfa	66	2000–2007 (7)	2007–2015 (8)	2012	−2.40	0.42	12	*Pinus echinata* Mill	37.5	−91.25	0.2	0.8
3	Cochran&Seidel	Cochran and Seidel (1999)	USA—Washington	Dsb	34	1965–1970 (5)	1970–1975 (5)	1973	−1.92	0.25	5	*Larix occidentalis* Nutt	45.098	−117.664	0.32	0.32
4	delRio_Fuencaliente	Contribution Miren del Rio	Spain—Central	BSk	54	2005–2010 (5)	2010–2015 (5)	2012	−1.68	0.5	5	*Pinus pinaster* Ait	38.473	−4.358	0.3	0.3
5	FGrOW_CM_22_08&22_09	Contribution FGroW Bjelanovic (2021)	Canada—Alberta	Dfc	22	2013–2016 (3)	2016–2021 (5)	2021	−1.93	0.46	3	*Populus tremuloides* Michx	54.573	−114.761	0.08	0.08
6	FVA_Bu224	Contribution FVA	Germany—BW	Cfb	103	2009–2014 (5)	2014–2019 (5)	2015, 2018, 2019	−1.83 −1.89 −1.80	0.71	5	*Fagus sylvatica* L	49.422	9.312	0.25	0.4
7	FVA_Bu226	Contribution FVA	Germany—BW	Dfb	101	1994–1999 (5)	1999–2004 (5)	2003	−1.98	0.79	5	*Fagus sylvatica*	48.638	10.062	0.5	0.5
8	FVA_Bu227	Contribution FVA	Germany—BW	Dfb	107	2009–2014 (5)	2014–2019 (5)	2015, 2018, 2019	−2.05 −1.79 −1.80	0.85	10	*Fagus sylvatica*	48.593	9.981	0.36	0.36
9	FVA_Bu229	Contribution FVA	Germany—BW	Dfb	109	2009–2014 (5)	2014–2019 (5)	2015, 2018, 2019	−2.04 −1.79 −1.77	0.74	5	*Fagus sylvatica*	48.564	9.953	0.9	0.9
10	FVA_Bu230	Contribution FVA	Germany—BW	Dfb	111	1994–1999 (5)	1999–2004 (5)	2003	−1.99	0.87	5	*Fagus sylvatica*	48.703	10.265	0.5	0.5
11	FVA_Bu247	Contribution FVA	Germany—BW	Dfb	54	2007–2012 (5)	2012–2017 (5)	2015	−1.77	0.78	5	*Fagus sylvatica*	48.968	8.525	0.41	0.43
12	FVA_Fi392	Contribution FVA	Germany—BW	Dfb	41	2007–2012 (5)	2012–2017 (5)	2015	−2.12	0.24	5	*Picea abies* H.Karst	48.729	10.216	0.1	0.1
13	FVA_Fi405	Contribution FVA	Germany—BW	Dfb	44	2005–2010 (5)	2010–2015 (5)	2015	−1.96	0.52	5	*Picea abies*	48.091	9.384	0.2	0.2

Table 1 (continued)

Nr	Experiment	Publication/contribution	Region/country	Koeppen climate zone	Tree age	Pre-drought inventory period	Drought inventory period	Drought year	$SPEI3_{Summer}$	Ratio SDI thinning vs control	Time since the last thinning	Main species	Latitude	Longitude	Plot area control	Plot area thinning
14	FVA_Fi411	Contribution FVA	Germany—BW	Cfb	61	2009–2014 (5)	2014–2018 (4)	2015, 2018	−1.75 −1.81	0.37	11	Picea abies	47.86	7.865	0.17	0.21
15	FVA_Fi414	Contribution FVA	Germany—BW	Dfb	47	1996–2002 (6)	2002–2008 (6)	2003	−1.82	0.44	6	*Picea abies*	47.871	8.046	0.23	0.32
16	FVA_Fi419	Contribution FVA	Germany—BW	Dfb	50	2007–2012 (5)	2012–2017 (5)	2015	−1.83	0.74	5	*Picea abies*	47.831	8.194	0.35	0.35
17	FVA_Fi442	Contribution FVA	Germany—BW	Dfb	43	2005–2010 (5)	2010–2016 (6)	2015	−1.89	0.8	22	*Picea abies*	48.25	9.124	0.14	0.14
18	FVA_Ki120	Contribution FVA	Germany—BW	Cfb	46	2005–2013 (8)	2013–2019 (6)	2015, 2018	−1.77 −1.74	0.32	NA	*Pinus sylvestris*	47.951	7.608	0.25	0.2
19	Harkas_30_28	Contribution Luke (Mäkinen & Isomäki 2004)	Finland—South	Dfc	54	1986–1994 (8)	1994–2011 (17)	1997, 2006	−1.66 −2.70	0.86	23	*Pinus sylvestris*	62.372	26.852	1.25	1.25
20	Arpvanha_376_19	Contribution Luke (Mäkinen & Isomäki 2004)	Finland—South	Dfc	93	1989–2003 (14)	2003–2015 (12)	2006	−2.65	0.63	14	*Pinus sylvestris*	62.069	24.491	2	2.5
21	Harkas_419_65	Contribution Luke (Mäkinen & Isomäki 2004)	Finland—South	Dfc	40	1991–2000 (9)	2000–2011 (11)	2006	−2.64	0.09	9	*Pinus sylvestris*	62.085	24.381	3.2	3.2
22	Harkas_420_1	Contribution Luke (Mäkinen & Isomäki 2004)	Finland—South	Dfc	60	1998–2005 (7)	2005–2012 (7)	2006	−2.39	0.31	7	*Picea abies*	61.216	24.517	1.25	1.25
23	Harkas_423_1	Contribution Luke (Mäkinen & Isomäki 2004)	Finland—South	Dfc	70	1992–1998 (6)	1998–2010 (12)	2006	−2.40	0.54	14	*Picea abies*	61.133	25.96	3	2
24	Harkas_425_3	Contribution Luke (Mäkinen & Isomäki 2004)	Finland—South	Dfc	36	1962–1967 (5)	1967–1974 (7)	1973	−1.73	0.61	5	*Picea abies*	61.217	25.993	1	1
25	Arpvanha_429_3	Contribution Luke (Mäkinen & Isomäki 2004)	Finland—South	Dfc	109	1989–2003 (14)	2003–2014 (11)	2006	−2.42	0.62	39	*Pinus sylvestris*	61.214	25.089	1.43	2.5
26	Arpvanha_446_44	Contribution Luke (Mäkinen & Isomäki 2004)	Finland—South	Dfc	114	1986–1996 (10)	1996–2012 (16)	2006	−2.46	0.82	10	*Pinus sylvestris*	61.395	25.053	2	2
27	Arpvanha_459_11	Contribution Luke (Siipilehto et al. 2021)	Finland—South	Dfc	55	1987–1999 (12)	1999–2019 (20)	2006, 2018	−2.55 −1.89	0.65	12	*Picea abies*	62.158	22.874	1.67	5

Table 1 (continued)

Nr	Experiment	Publication/ contribution	Region/ country	Koeppen climate zone	Tree age	Pre-drought inventory period	Drought inventory period	Drought year	SPEI3$_{Summer}$	Ratio SDI thinning vs control	Time since the last thinning	Main species	Latitude	Longitude	Plot area control	Plot area thinning
28	Arpvanha_474_1	Contribution Luke (Mäkinen & Isomäki 2004)	Finland—South	Dfc	58	1987–1996 (9)	1996–2006 (10)	2006	−2.54	0.5	9	*Pinus sylvestris*	62.177	22.832	1	1
29	Harkas_8_5	Contribution Luke (Mäkinen & Isomäki 2004)	Finland—South	Dfc	63	1994–2003 (9)	2003–2011 (8)	2006	−2.67	0.33	9	*Picea abies*	62.145	24.713	2	1
30	Moreno	Moreno Fernandez et al. (2021)	Spain—Central	BSk	34	1998–2002 (4)	2002–2007 (5)	2005	−1.91	0.45	8	*Quercus pyrenaica* Willd	40.9	−3.85	0.32	0.32
31	Neumann&Hasenhauer	Neumann and Hasenauer (2021)	Austria—Vienna	Dfb	100	2009–2014 (5)	2014–2019 (5)	2015	−1.75	0.27	5	*Quercus petraea* (Matt.) Liebl	48.22	16.24	0.25	0.2
32	Powers	Powers et al. (2010)	USA—Minnesota	Dfb	50	1962–1967 (5)	1967–1972 (5)	1970	−2.08	0.17	5	*Pinus resinosa* Ait	47.7	−91.933	0.72	0.72

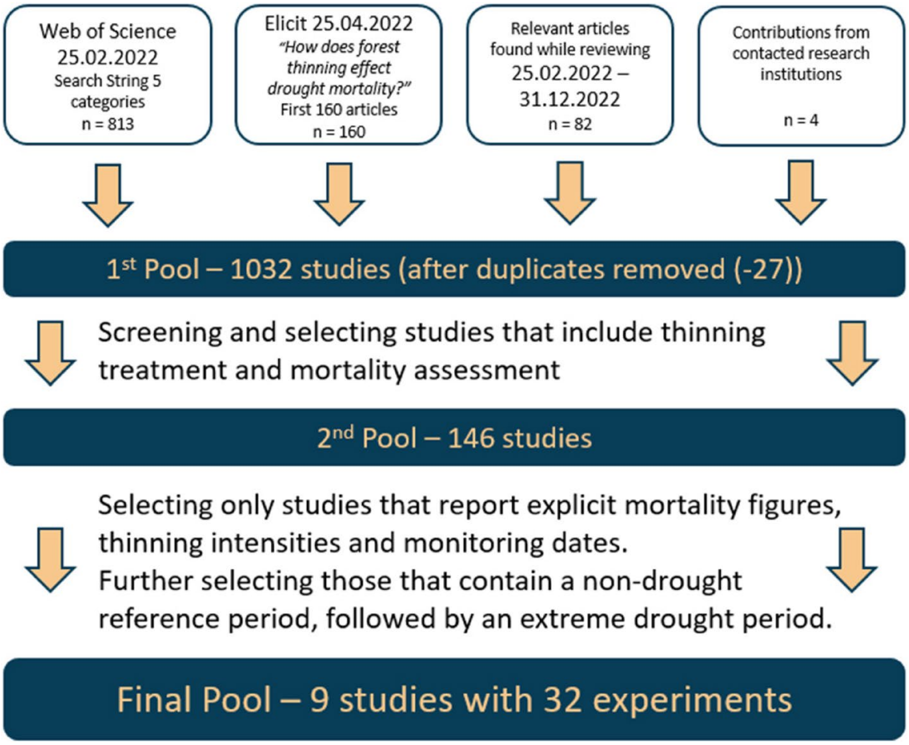

Fig. 1 PRISMA flow chart displaying sources and steps of literature review up to selection studies for the meta-analysis

confounded by other stressors or disturbances such as windthrow or fire. In a first screening step, we reviewed titles and abstracts of the publications and discarded irrelevant studies, resulting in a second pool of 146 studies (Fig. 1). Subsequently, we assessed whether the studies reported the timing of thinning activities and tree mortality. If this information was not available, we approached the corresponding author to request it. We carefully assessed, whether the studies distinguished between tree mortality and removals due to thinning or other management practices and discarded them if that was not the case. Mortality was mostly not assessed on an annual basis, but rather at the end of various inventory periods which differed greatly in their intervals (1–20 years).

2.2 Selection of drought periods

To analyse the influence of drought intensity on thinning effects related to mortality, we selected drought events using the TERRACLIM database (Abatzoglou et al. 2018) which offers historic climate data at a monthly resolution with a spatial resolution of 1/24 degree (~4 km) beginning in 1958. For each experimental location, we calculated the average Standardized Precipitation Evapotranspiration Index (SPEI) value for three summer months (June, July, and August) for years with data on mortality, in the following called SPEI3Summer (Vicente-Serrano et al. 2010). Subsequently, we checked if SPEI3Summer reached values below −1.65, which we defined as the threshold for extreme drought years (Agnew 2000). For each experiment, we selected the inventory periods that included extreme drought years to capture mortality that was potentially induced by the extreme drought. These periods are subsequently labelled inventory period with drought event (IPD).

We used the inventory period immediately before a determined IPD as a reference period for stand conditions, but only if it did not comprise extreme droughts (SPEI3Summer < −1.65) and not more than one severe drought, SPEI3Summer < −1.28 (Agnew 2000). We used the reference period to contrast the occurrence of mortality under "normal" conditions with that observed in inventory periods with an extreme drought event. This reference period is subsequently labelled inventory period before drought event (IPB). If an experiment showed no suitable combination of IPB and IPD, it was discarded from the analysis. If an experiment showed more than one suitable combination, we took the combination in which the difference in SPEI between the IPB and IPD was the most pronounced.

When trees' vitality declines gradually for several years after a drought event or when a drought event occurs towards the end of an inventory period, mortality may not be fully captured within the IPD. To account for these potential lag effects in mortality, we analysed the risk ratio in the inventory period that followed the IPD, hereafter labelled inventory period after drought event (IPA). We excluded IPAs that contained a drought period, therefore, the lag-effect analysis could only be performed on a subset of the original dataset.

Since we were bound to the variable inventory intervals of the various studies, the selected IPBs, IPDs and IPAs do not display the same length both across and within studies. However, for the purposes of our analysis of mortality rates, it is only necessary that both treatments (thinned and unthinned) had been remeasured at the end of the same interval to make them comparable.

Our selection procedure yielded a final pool of 32 experiments for the meta-analysis (Fig. 1, Table 1). A large share of data stems from two major contributions: nearly 50% (15 of 32 experiments) were from research sites of the State Forest Research Institute of Baden-Württemberg (FVA) and another 34% (11/32) of thinning experiments of the Natural Resources Institute of Finland (Luke). Geographically, the selected experiments were distributed mostly in clusters, in Central Europe, Finland, and in North America (Fig. 2), thus covering a large climatic gradient. The experiments comprised 12 tree

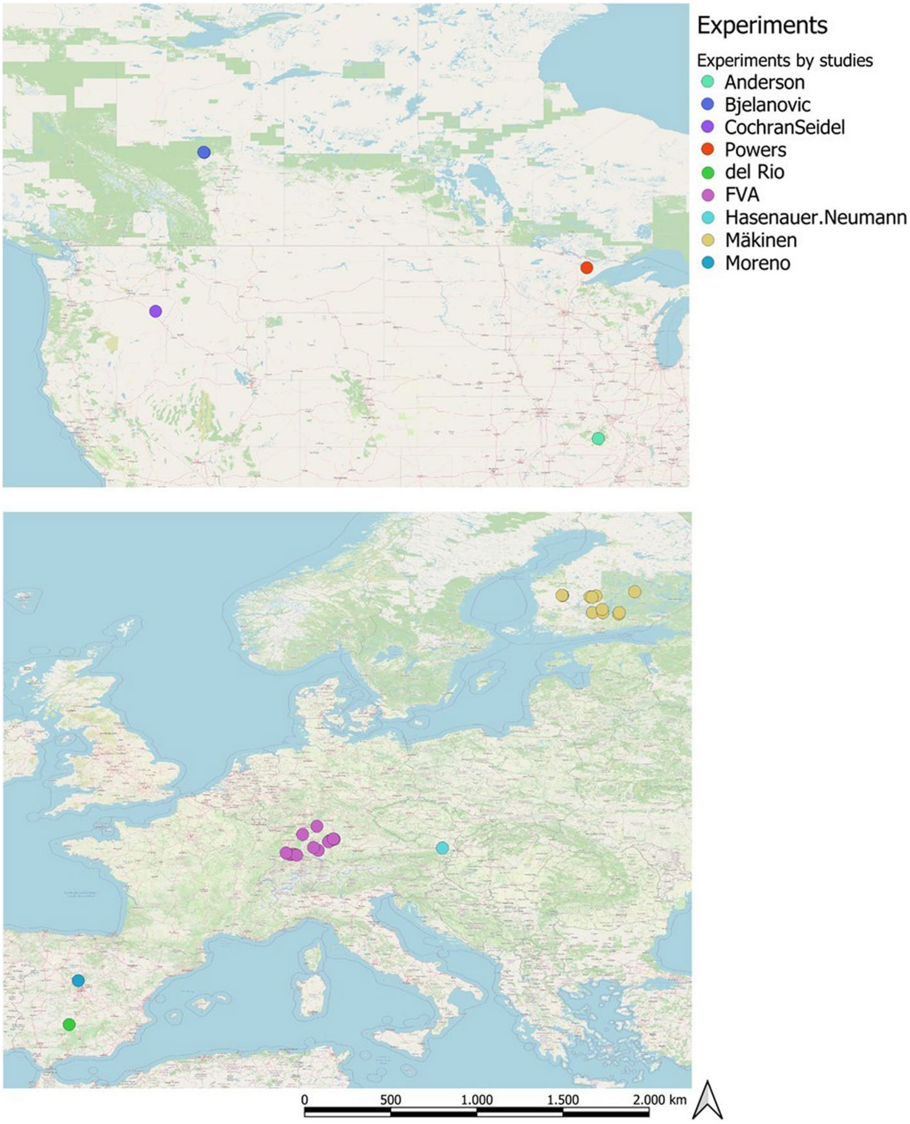

Fig. 2 Maps of experiments selected for the meta-analyses in North America (top) and Europe (bottom); markers represent experiments and markers with the same colour represent experiments within studies

species (Table 1), of which four belong to the genus *Pinus* and three to the genus *Quercus*.

2.3 Selection of treatment intensity

For experiments that included several thinning treatments, we limited the analysis to the control and the most intensive thinning treatment, since the potential thinning effect was reported to be most pronounced in heavy treatments (Sohn et al. 2016). We quantified the intensity of individual treatments by comparing the stand density index (SDI, Reineke 1933) of the thinned treatment to that of the control. SDI estimates stand density depending on the number of stems per ha and their diameters. It allows the comparison of relative densities of thinned stands to their control in experiments across different forest types and age classes.

2.4 Meta-analysis

Our aim was to conduct a meta-analysis based on mean values to compare mortality rates between controls and treatments in thinning studies. Since the mortality rate is assessed at the stand level, there is just one value per research plot and no standard deviation (SD), unless plots are replicated. Yet, for this approach a SD is necessary to account for the precision of the studies included in the meta-analysis and to calculate the pooled size effect. Accordingly, we faced the limitation that most studies did not report SD values on mortality because they were not designed to analyse stand-level tree mortality rates and therefore lacked replication at the stand level. To circumvent this issue, we employed an approach that estimates the effect size and its variance from the absolute stem number, dead and alive, of the thinned and control treatment for each experiment. These values were summarised in 2×2 contingency tables (Borenstein et al. 2009, Appendix Table 4). The effect size, the so-called risk ratio, is characterised as the mortality rate in thinned treatments divided by the mortality rate in control treatments (Borenstein et al. 2009, Eq. 1).

$$\mathrm{RR} = \frac{\text{Mortality rate thinned}}{\text{Mortality rate control}} = \frac{\frac{A}{N_1}}{\frac{B}{N_2}} \tag{1}$$

where A is the number of dead trees, N1 the total number of trees in the thinning treatment, B the number of dead trees, and N2 the total number of trees in the control treatment.

In their review on meta-analyses in the field of plant ecology, Koricheva and Gurevitch (2014) stated that the risk ratio analysis, originating from medical research, is a useful but rarely used tool. They list Hyatt et al. (2003) and He et al. (2013) as examples for utilising the risk ratio method for analysing the survival of trees or plants in relation to density and other stressors. Since this method does not require a measure of variance, such as standard deviation associated with the mean response, we were able to include many publications that would otherwise not have been used in the meta-analysis approach based on mean values. As a result, we achieved a much higher coverage of forest types and regions.

In the risk ratio analysis, variance and standard error are calculated based on sample size, which in this case refers to the number of trees per stand. However, this procedure has the drawback that stands with a greater number of stems per area, e.g. young stands or coppice forests, may yield a more precise estimate thus skewing the mean effect size in the meta-analysis. This could bias the results by disproportionately emphasising young stands, which typically exhibit a higher mortality than older stands through stem exclusion. To address this, we implemented an additional weighting procedure that evaluates experiments according to their total plot area rather than stem numbers. This procedure is independent of tree age and site location. We scaled the total plot area for each experiment, divided this value by 2, and multiplied it by the inverse of the number of experiments, to derive a correction value (Eq. 2). In cases where the plot area of an experiment was larger than the mean of all experiments, the weight would be higher and vice versa. Given the disproportionate distribution of plot area among experiments, a few large plots would have had strongly influenced the result. Therefore, we selected a factor of 2 for dividing the scaled plot area in an iterative process to mitigate the impact of the weight. Lastly, this weighing factor was added to the factor that would have been used in an unweighted analysis, which is also the inverse of the number of experiments (Eq. 3).

Correction factor for the weight:

$$cw = \frac{1}{k} \times \frac{\text{scaled plot area}_i}{2} \tag{2}$$

Weight for the effect sizes:

$$w = \frac{1}{k} + cw \tag{3}$$

where k is the number of experiments.

To check the sensitivity of this approach to the weighing factor, we performed the analyses with and without this weighting. In the analysis without weighting the effect sizes differed only marginally. Although the weighting did not influence the direction of the outcome, we decided to display the more accurate analysis with our weighting procedure.

The meta-analysis was performed with R software (R Core Team 2022) using the "metafor" package, specifically the function *rma* (Viechtbauer 2010). Inventory periods with no mortality in the control and the thinning treatments were discarded from the analysis, because the calculation would have led to an unreliable risk ratio (Higgins et al. 2019). If the mortality in either the thinned or control treatment (A or B in the 2 × 2 table, Appendix Table 4) was zero, we utilised a correction factor by adding 0.5 to the dead and living individuals in both treatments (all cells in the 2 × 2 table) (Fleiss & Berlin 2009).

We applied a random-effects model and used the "Restricted Maximum Likelihood" method for estimating the variance (Harrer et al. 2021; Viechtbauer 2005).

The effect sizes of single experiments, from now on called risk ratios, were pooled to compute the mean effect size across all experiments, from now on labelled pooled risk ratio. In this step, the weight of the single studies defined their specific impact on the pooled risk ratio. We chose 95% as confidence interval level for our analysis. In addition to the pooled risk ratio and its confidence interval, we analysed the measures of between-study heterogeneity of the meta-analyses. We opted to apply Higgins and Thompson's I^2 statistic (I^2 in the following) as a measure of heterogeneity, which quantifies the portion of the variance that cannot be explained by sampling error (Higgins & Thompson 2002). We adopted this statistic, because it is independent of the number of experiments, thereby allowing for comparisons between meta-analyses. Additionally, it is easier to interpret, as it is expressed as a percentage. For example, Higgins & Thompson (2002) suggest that I^2 values > 75% can be interpreted as substantial heterogeneity.

2.5 Comparison of pre-drought and IPDs

We expected that the risk ratio of thinning experiments should typically be below 1 because background mortality rates in unthinned stands should be higher than in thinned stands as a result of higher density-dependent self-thinning from competition (Monserud et al. 2004). Therefore, we not only assessed the risk ratio per se, but also how it changes from a "normal" pre-drought period to a drought period. In this manner, we performed two separate risk ratio meta-analyses for IPB and IPD, meaning one meta-analysis for all IPBs and one for all IPDs. Accordingly, both meta-analyses were comparable as they contained identical experiments, but different inventory periods. Subsequently, we compared the pooled risk ratio, between IPBs and IPDs. We also analysed the risk ratios of the single experiments and their distribution with the assistance of forest plot analyses, to check for patterns within experiments of the same study, region or those containing the same species. For the interpretation of meta-analyses, forest plots (e.g. Fig. 3) were used to visualise the observed effects of individual studies, their confidence interval and their weight. To avoid confusion, the term "forest plot" will be only used for this type of diagram and not for experimental sites, which are often also referred to as plots.

2.6 Accounting for variance with covariates

We identified several covariates that helped explain variance of the influence of thinning on mortality in similar studies (Appendix Table 5) and tested for significance through meta-regressions using the function *rma* of the metafor package in R (Viechtbauer 2010). We conducted the meta-regression for both meta-analyses, to see if the impact of these covariates changes between non-drought and drought conditions. Taxonomic class played an important role in explaining differences in drought responses in other studies (Cailleret et al. 2017; DeSoto et al. 2020; McDowell et al. 2008; Sohn et al. 2016; Steckel et al. 2020). Moreover, we checked the effect of thinning intensity, calculated as the ratio of SDI in thinned to SDI in control treatments, on the risk ratio in both periods. SDI values were calculated for the start of each period. Other covariates specifically mentioned by other studies, such as time since last thinning intervention (Sohn et al. 2016), stand age (D'Amato et al. 2013; Lucas-Borja et al. 2021; Steckel et al. 2020), and regional climate (Gleason et al. 2017; Schmitt et al. 2020) in terms of main groups of Koeppens climate classification, were also investigated. Finally, we looked for the effects of interactions between covariates on mortality response using multi-variable meta-regression models.

We recognise that the actual thinning method, e.g. thinning from above or below, can have an important influence on the exposure of crowns of dominant canopy trees or intermediate and suppressed sub-canopy trees. Yet, we did not include thinning method as a factor in our analysis because (a) information on the thinning methods used was not available for all studies; (b) in some cases, it would be challenging to clearly assign a method, as different thinning methods are combined during stand development within the same thinning regime, e.g. switch from thinning from above to thinning from below; and (c) the overall number of studies was too low to obtain reliable results for different types of thinning methods.

2.7 Dominance Index

To assess whether thinning increased the mortality of dominant trees in response to extreme droughts, we

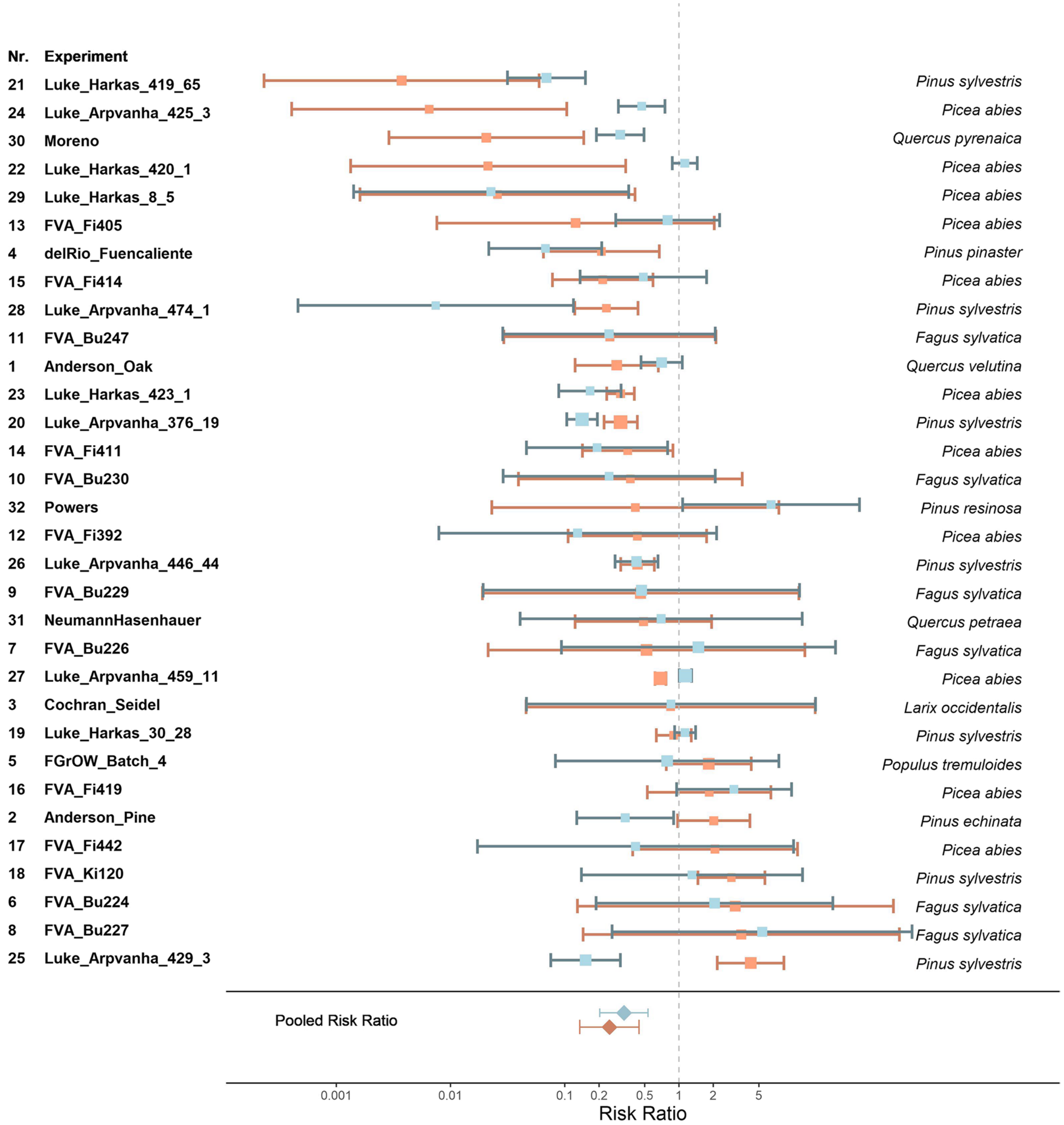

Fig. 3 Forest plot of pre-drought period (blue) and drought period (orange) effect sizes. Effect size is the risk ratio; *x*-axis is in log scale; size of square represents the weight; the lower the effect size, the lower is the mortality rate in thinned stands relative to their control. The experiments are ordered from low to high-risk ratio during IPD

applied the Dominance Index developed by Meyer et al. (2022) to identify the average dominance of trees which died in different periods and treatments. This Dominance Index is characterised as the ratio of mortality rate based on stem numbers in relation to the mortality rate based on basal area (Meyer et al. 2022):

$$\frac{\text{Mortality rate stems}}{\text{Mortality rate basal area}} = \text{Dominance Index} \qquad (4)$$

If the proportion of the number of dead stems is higher than the proportion of dead stems' basal area, the Dominance Index exceeds 1, meaning that mostly smaller, below average size trees had died (Eq. 4). Since the Dominance Index is a measure relative to average stem size, it allows comparison between stands with different diameters. This aspect is particularly useful for our analysis as thinning operations may have altered the average diameters of trees compared to control treatments. We calculated the dominance index for the IPD and IPB split by treatment and used the Wilcoxon test to assess significant differences between the groups. Note that the index can only be calculated in inventory periods that reported mortality. A subset of 15 studies were suitable for calculating the Dominance Index, as data on both the number of stems and basal area per thinning treatment was needed for its calculation.

Table 2 Pooled risk ratios, characterising the ratio of mortality in thinned and unthinned stands from the pre-drought period to drought period, each consisting of the same 32 experiments. Drought-periods were selected with SPEI3$_{\text{Summer}}$ as described above. Between-study heterogeneity I^2 quantifies how much of the variance cannot be explained by the sampling error

Inventory period	Pre-drought	Drought
Pooled risk ratio	0.329	0.246
Confidence interval of risk ratio	0.202–0.536	0.135–0.446
Significance for difference from 1	< 0.0001 ***	< 0.0001 ***
I^2 (between-study heterogeneity)	93.25%	94.00%

Significant levels used were $p < 0.05$ = *, $p < 0.01$ = ** and $p < 0.001$ = ***

3 Results

3.1 Risk ratio before and after drought

The risk ratios denote the mortality risk of trees in thinned treatments relative to the risk of trees dying in the control, so that a value of 1 implies no effect. The random effects models for both meta-analyses were statistically significant and estimated confidence intervals that were clearly below 1. Before the drought event, the pooled risk ratio was 0.329 (Table 2), with confidence intervals (CI) ranging from 0.202 to 0.536. In the inventory periods that contained a drought event, the risk ratio was 0.246 (CI 0.135–0.446) (Table 2). Accordingly, the risk of trees dying was 67% lower in thinned treatments compared to the control before the drought and 75% lower in the drought inventory period (Table 2). However, as the confidence intervals of IPB and IPD overlap (Fig. 3, bottom), the difference cannot be considered statistically significant. Examining a third period following the IPD to assess lag mortality yielded no further significant differences, likely due to the low number of experiments (12), insufficient to attain a statistically significant result (analysis in Appendix).

There was substantial heterogeneity between experiments, revealed by the very high I^2 in both meta-analyses (Table 2). The risk ratios of the various experiments were also not distributed closely around the calculated pooled risk ratio, owing the variability of mortality rates between periods and experiments (Appendix Fig. 10). For example, the risk ratios of some experiments were greater

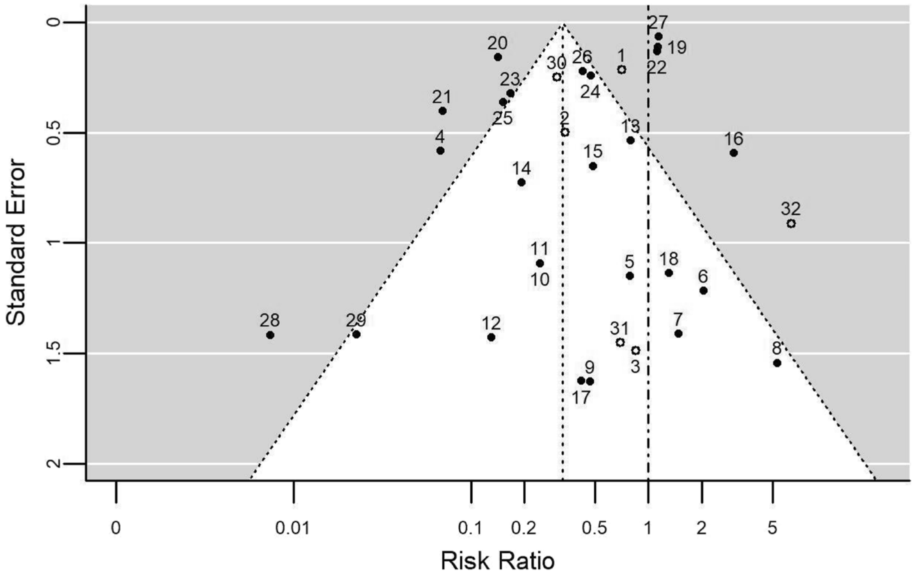

Fig. 4 Funnel plot of the meta-analysis of the pre-drought inventory period. Risk ratios and standard errors of single experiments are depicted on the x- and y-axis, respectively. Published studies are depicted as open circles and contributions as closed circles. The evenly dotted line in the middle of the triangle depicts the pooled risk ratio. The scattered dotted line at $x = 1$ indicates no effect. To the left of it, mortality is lower in thinned stands

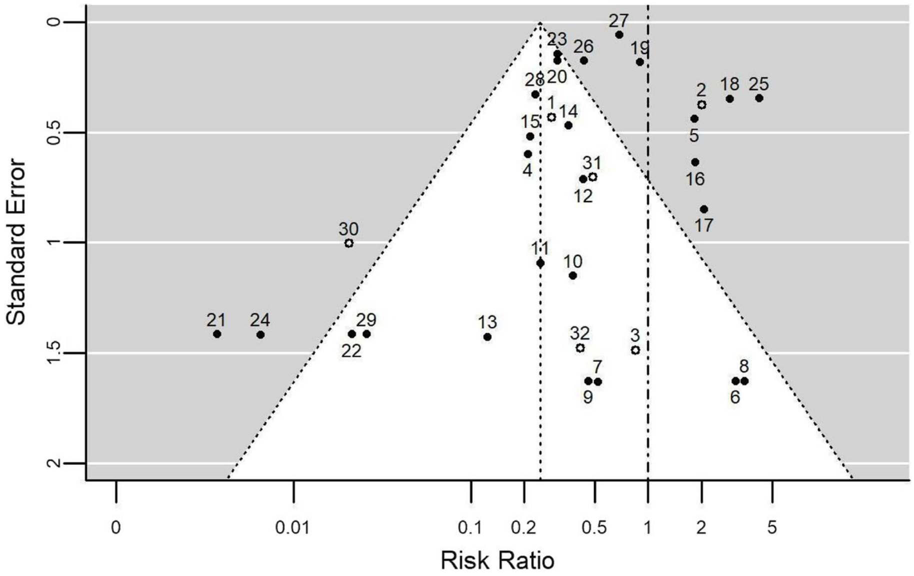

Fig. 5 Funnel plot of the meta-analysis of the drought inventory period. Risk ratios and standard errors of single experiments are depicted on the *x*- and *y*-axis, respectively. Published studies are depicted as open circles and contributions as closed circles. The evenly dotted line in the middle of the triangle depicts the pooled risk ratio. The scattered dotted line at $x=1$ indicates no effect. To the left of it, mortality is lower in thinned stands

than 1, showing an opposite effect from the pooled risk ratio (Fig. 3). Funnel plots for the IBP and IPD (Figs. 4 and 5) indicate that the heterogeneity is driven by high standard errors of experiments (due to low sample numbers). Nevertheless, experiments with higher precision (low standard error) exhibit a high spread around the mean effect size. Further, risk ratios of experiments with lower standard errors are not evenly centred around the pooled risk ratio but appear to deviate towards a higher risk ratio for the IPD. While some experiments showed no change in risk ratio and standard error from IPB to IPD (e.g. experiments 19, 8, 3 or 29), in other experiments both shifted considerably. Differences in standard error (*y*-axis, Figs. 4 and 5) can be explained by the absence of or very low mortality. In experiments in which the absolute stem number of dead trees was 0 or 1, the standard error increases immensely (to around 1.5) in the risk ratio method. The standard errors of some experiments shifted between inventory periods from high to low (e.g. exp. 28) or vice versa (e.g. exp. 22), because in one period mortality was absent or very low but not in the other. Altogether, the high heterogeneities in our meta-analysis models were due to the unusual spread around the pooled risk ratio and the absence of, or very low mortality that led to a high standard error. We could not detect a pattern in the distribution of published studies that would indicate a publication bias towards studies that documented an effect of thinning on mortality.

3.2 Influence of covariates on thinning effects on drought-related mortality

Thinning intensity had a positive (but not significant) influence on the risk ratio (Appendix Table 5) for both periods. This suggests that the greater the difference in stand density between treatments, the lower the mortality in thinned compared to the control treatment (Fig. 6). Yet, the R^2 value, which states how much of the heterogeneity is explained by the covariate, is only 4.2% in the IPB and 0 in the IPD. Similarly, the coefficient of time since last thinning was positive, alas not statistically significant. The positive relationship indicates relatively lower mortality in thinned stands compared to the control when the thinning was executed recently (Fig. 7). The R^2 value for time since the last thinning was 0 before drought and 3.0% in the IPD. The subgroup analysis of Koeppen Climate Zones revealed that in both periods experiments from warm/arid and continental climates had a risk ratio significantly lower than 1, whereas experiments in temperate zones displayed mixed results (Fig. 8, Appendix Table 5). For the IPD, the Koeppen Climate Zones could explain 11.3% of the variation, whilst the R^2 for IPB was 0. In this context, however, one has to keep in mind that there were few experiments in warm/arid (2) and temperate zones (3).

Regressions that tested the influence of age, taxonomic class or species did not contribute to explaining the variance ($R^2=0$). In our analysis of meta-regressions with multiple predictor variables, we also could not find that

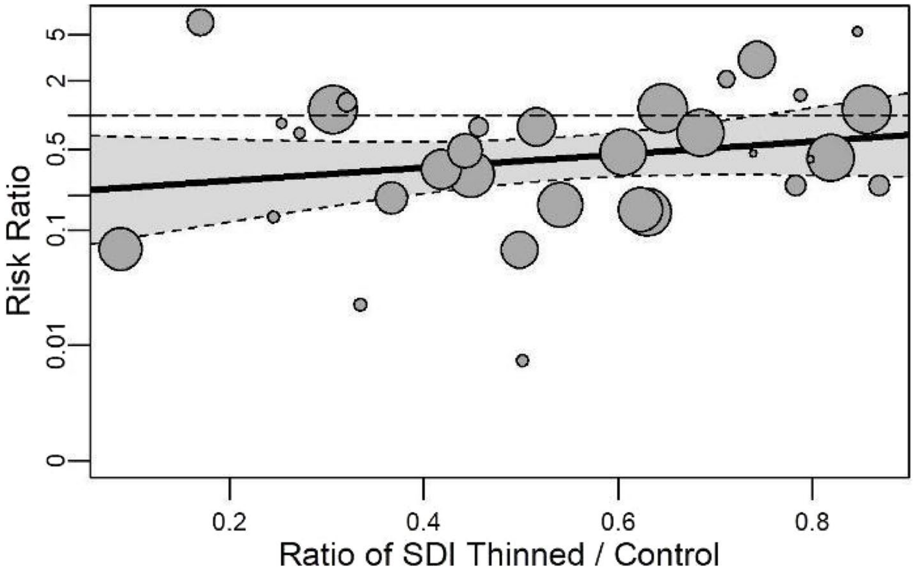

Fig. 6 Meta-regression of risk ratio and thinning intensity measured as ratio of stand density index in thinned and control stands in the inventory period before drought, values below 1 indicate a lower mortality rate in thinned treatments, the intercept is weakly significant ($p < 0.05$), the slope not. The size of the dot indicates the weight calculated from the variance of the respective experiment

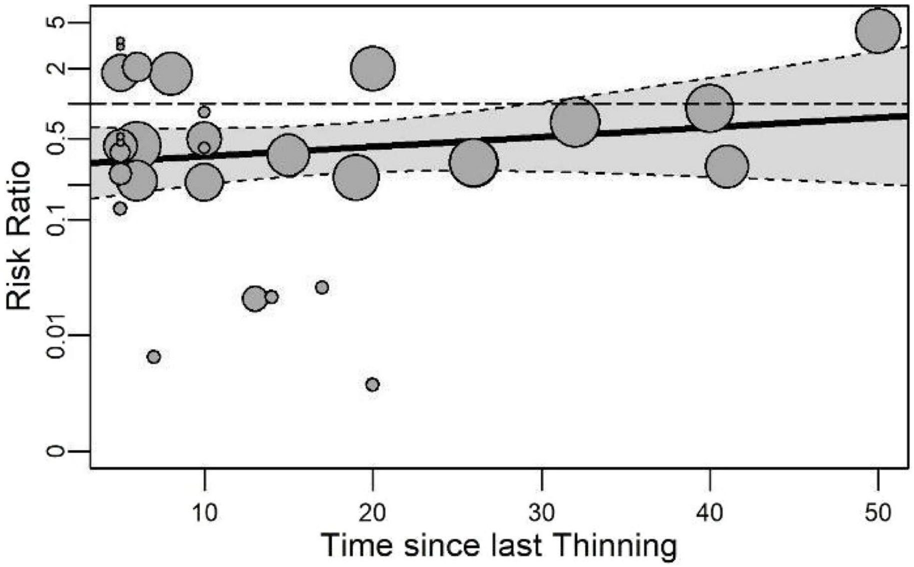

Fig. 7 Meta-regression of effect size (risk ratio) and time since last thinning in years in the inventory period before drought, values below 1 indicate a lower mortality rate in thinned treatments, the intercept is weakly significant ($p < 0.05$), the slope not. The size of the dot indicates the weight calculated from the variance of the respective experiment

interactions among covariates improved the explanation of the variability.

3.3 Dominance Index

The Dominance Indices of the experiments did not differ between controls and thinned treatments after the drought (Fig. 9). For the IPB, the Dominance Index of controls was slightly and significantly higher than the one of the thinned stands, indicating that on average more suppressed trees died in the controls than in the thinned stands. The mean dominance indices were above 1 in all treatments, indicating that dead trees were relatively smaller compared to the average tree size of a given forest stand. However, across all treatments and periods, the

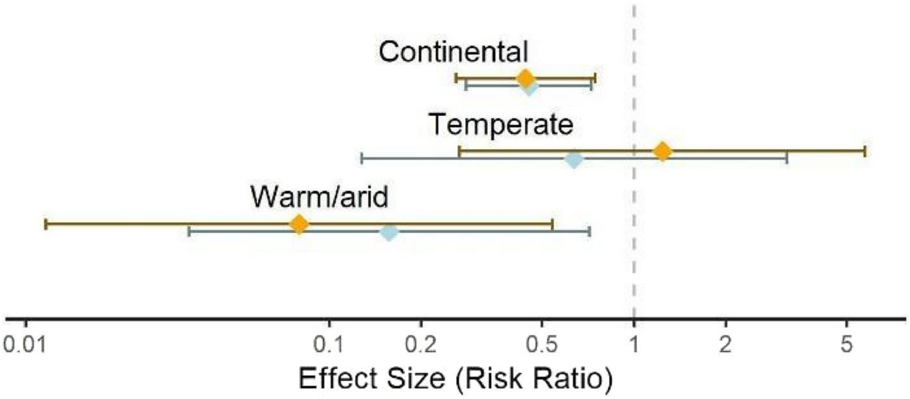

Fig. 8 Forest plot of the subgroup analysis of Koeppen Climate Zones with effect size of pre-drought periods (blue) and drought periods (orange). Effect size is the risk ratio; the *x*-axis is in log scale; the lower the effect size, the lower is the mortality rate in thinned stands relative to their control. There are 2 experiments in the warm/arid zone, 3 in the Temperate zone and 27 in the Continental zone

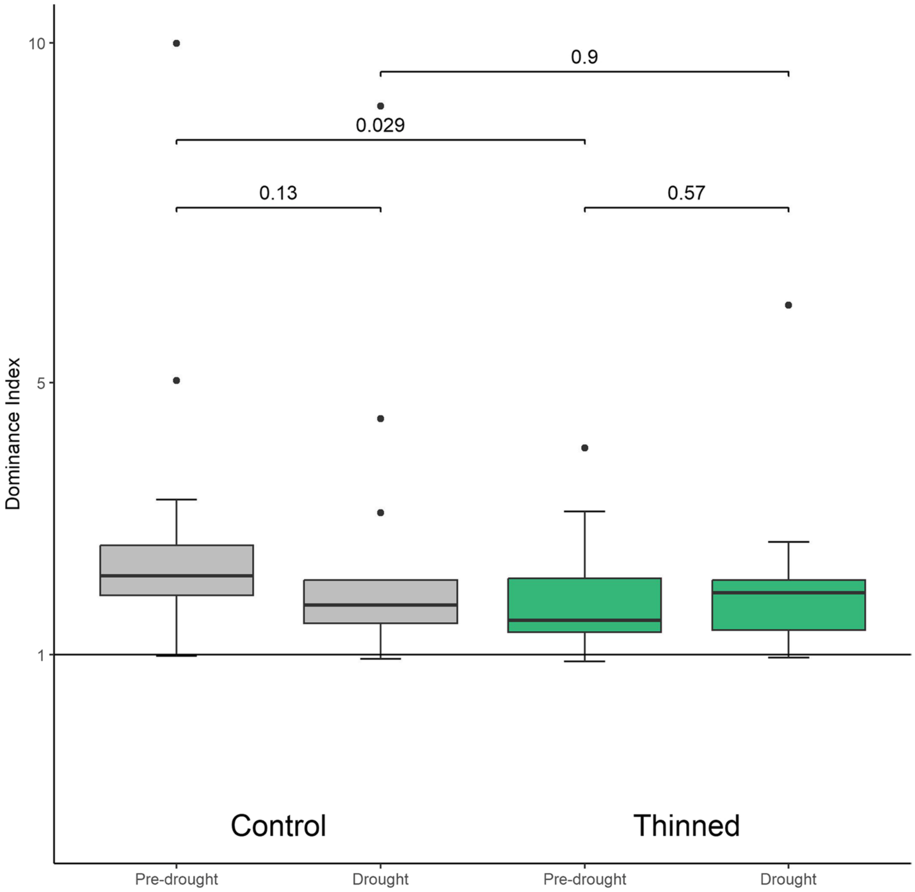

Fig. 9 Dominance Index before and after drought in control (grey) and thinned (green) treatments. Values above 1 indicate a lower dominance of trees that died when compared to living trees of the same stand; brackets with *p*-values indicate the significance of differences between groups tested with the Wilcoxon test

Dominance Index was not significantly different from 1. Thus, there were also some cases, where more dominant trees had died as visualised in the error bars reaching below 1 (Fig. 9, Appendix Table 6). We have to keep in mind, however, that the Dominance Index is a relative measure and the average diameter in thinned stands was higher than in control stands, because overtopped and intermediate trees were preferably removed in preceding thinning operations (average diameter pre-drought: control = 21.0 cm, thinning = 25.7 cm, details see Appendix Table 6).

4 Discussion

Our literature search confirmed that the influence of forest management on tree mortality is a very important and frequently mentioned topic, as we found more than 1000 papers in total with different search approaches. However, most studies (98% of the screened publications) did not investigate mortality per se or not in a way that permitted the use of reported data in this meta-analysis. Typically, mortality was mentioned in the introduction (sometimes also in the abstract) as well as in the discussion while the paper itself was about the growth response of surviving trees. Those studies that assessed mortality rarely reported or presented explicit data. However, we could still make use of studies by calculating the mortality data ourselves from tables or by extracting them from figures published in the respective papers.

4.1 Thinning does not increase tree mortality after extreme droughts

Previous research has shown that thinning can improve tree growth by reducing stand-level transpiration and interception, and increasing soil water availability for individual trees (Breda et al., 1995; del Campo et al. 2022; Gebhardt et al. 2014; Sohn et al. 2016). This suggests a reduced risk of drought-related mortality. In this study, thinning reduced the overall mortality risk of trees. However, we found no statistically significant difference in the risk ratios before and after the drought event. This means that, contrary to our expectation, the lower mortality rate in thinned stands relative to unthinned stands in pre-drought periods was not further reduced during and after extreme drought events. Yet, other studies documented higher risks of growth decline or mortality if larger growing space was available, because their crowns are more exposed to radiation and therefore transpiration and soil water depletion increase locally during drought periods (Brooks & Mitchell 2011; Jump et al. 2017; Bosela et al. 2021; Stovall et al. 2019; Taccoen et al. 2021; Trugman et al. 2018). Our results show that there is no substantial difference in the relative dominance of dead trees between control and thinning treatments before and after droughts, which confirms findings of other studies that documented mainly suppressed trees dying in thinned treatments (e.g. Knapp et al. 2021; Kulha et al. 2023). A higher vulnerability of suppressed trees may be a result of asymmetric belowground competition with dominant trees, which might consume disproportionately more soil water and nutrients, leaving suppressed trees to situations of insufficient water supply for survival (Fernández-de-Uña et al. 2023; Trouvé et al. 2014). Higher storage capacity of carbon could enable more dominant trees to withstand droughts longer and defend themselves better against biotic attacks (Fernández-de-Uña et al. 2023).

4.2 Potential of covariates in explaining the high variability

The high variability across experiments observed in our analysis, even for experiments with a robust number of samples (thus low standard error) (Figs. 4 and 5) suggests that there is no generalizable effect of thinning on drought-related mortality across all analysed experiments. There are obviously different mortality response patterns to thinning in different regions and forest types. Two meta-analyses that assessed the effect of stand density on drought response in terms of growth and hydraulics found similar results on between-study heterogeneity ($I^2 > 90\%$) (Castagneri et al. 2021; del Campo et al. 2022).

Tree species identity and taxonomic class were significant covariates on different hydraulic processes in the meta-analysis of del Campo et al. (2022) and in two studies investigating growth response after thinning and drought (Bottero et al. 2021; Sohn et al. 2016). In the results of the meta-analysis of Castagnieri et al. (2021), however, these factors did not explain much of the variation. Likewise, we could not detect significant differences between tree genera and taxonomic classes. Differences in physiological drought reactions and vulnerability to pests between tree species (Cailleret et al. 2017; DeSoto et al. 2020; McDowell et al. 2008) support the idea that we should also see these differences in a meta-analysis on mortality responses to drought.

Climatic conditions at experimental sites, based on a broad characterisation of Koeppen climate zones, were the strongest explanatory covariate for mortality response ($R^2 = 11.3\%$), but only during IPDs. Climatic site conditions also contributed significantly to explaining heterogeneity in the meta-analysis of del Campo et al. (2022), not limited to drought periods and with higher R^2 values (11–40%). The positive effect of thinning in reducing mortality declined from warm to continental to temperate sites. This observation contradicts the theory that tree growth on dry sites would be limited through water scarcity so intense that reducing competition would not lead to a substantial improvement in growth (Gleason et al. 2017). At dry sites, trees that are better adapted to droughts may well be able to benefit from increased growing space (Schmitt et al. 2020).

Our meta-regression analysis indicates that the risk of mortality decreases with thinning intensity (significantly in pre-drought conditions). Thinning intensity refers here to the effective reduction in stand density in comparison to unthinned control stands. It does not necessarily describe the intensity of tree removal in a single thinning operation. There may be good reasons to limit the intensity of single thinning operations and to reduce or maintain stand density through more frequent thinning interventions of lower intensity. The latter approach is known to limit a possible undesirable increase in the vulnerability to storm damage following thinning (Mason & Valinger 2013). It may also help to reduce the negative effects of increased transpiration stress resulting from sudden exposure of the remaining trees, commonly referred to as "thinning shock" (Garber et al. 2011). Many studies reporting on growth response or water relations confirmed that the positive effect of thinning increases with intensity (Bucher et al. 2023; del Campo et al. 2022; Gebhardt et al. 2014; Sohn et al. 2016). The stronger the reduction in stand density, the greater interception and transpiration would be reduced, thereby resulting in higher soil water content and lower mortality.

In our and in many others studies (del Campo et al. 2022; Sohn et al. 2016), the effect of thinning on drought response decreased with time since the last thinning. A study in *Cedrus atlantica* G. Manetti forests in France documented improved growth recovery from drought up to ten years following thinning (Guillemot et al. 2015), whereas a global study estimated soil moisture and transpiration to be enhanced for three to eight years following thinning (del Campo et al. 2022). Apparently, the crowns of the remaining trees eventually close the gaps in the canopy, thereby the interception and the transpiration rate once again increases. How quickly the crowns fill this growing space created by thinning has not been extensively studied. This process will likely vary with tree species, tree growth rate, site quality, and the question of whether trees fill the belowground gaps and thereby increase their water uptake concomitantly. Interestingly, age did not significantly influence the heterogeneity of thinning responses, despite a wide range of stand ages in our study.

Only a small proportion of the heterogeneity in thinning responses in our meta-analyses could be explained with selected covariates. Perhaps, there are covariates which were not included in our analysis, since they are not easy to measure and thus barely reported, which might explain more of the heterogeneity. Above all, soil water holding capacity is proven a highly relevant factor for mortality response to drought (Callahan et al. 2022; Klesse et al. 2022). We may not have discovered interactions among covariates owing to the small sample size (and we tested only simple interactions to avoid overfitting the meta-regression models (Higgins & Thompson 2004)). Potentially, important interactions among covariates that we could not analyse comprise those between species and site, as trees of the same species can respond quite differently to drought depending on site conditions (Trugman et al. 2021).

4.3 Study limitations and research outlook

Drought-related tree death arises from an interplay of tree physiology, site factors and biotic factors (Anderegg et al. 2015; Hartmann et al. 2022; Trugman et al. 2021). Our current analysis does not capture the influence of biotic agents and possible pre-disposing factors, such as previous droughts. Biotic agents are often secondary stressors that attack weakened trees (Anderegg et al. 2015; Hartmann et al. 2022). Nonetheless, damaging insects may target trees of specific sizes regardless of their stress level, or become epidemic for reasons other than drought (Trugman et al. 2021), such as the availability of fresh breeding material for bark beetles after wind throw. Thus, to improve future analyses of thinning effects on drought-related mortality, one would have to know the precise cause of mortality (drought, pest, disease, etc.), which is rarely assessed. We based our analysis on the definitions of tree mortality provided in the individual studies. Apart from excluding studies that did not distinguish between natural tree mortality and harvesting removals, we were unable to assess all different options to account for natural tree mortality—for instance, whether trees broken at the stem base were classified as dead. More importantly, based on the documentation, we could not determine whether trees of low vitality and on the verge of dying were preferentially removed during thinning in these studies. This practice would have pre-empted natural mortality and thus influenced the reported mortality rates in thinned stands.

It is possible that our drought selection procedure did not accurately represent the actual drought situation at a given site. The Terraclim database is very useful for obtaining homogenised climate data to compare studies that are spread globally. However, the coarse resolution does not allow to account for microclimatic deviations (Zang et al. 2020). Furthermore, the SPEI does not take into account soil depth and water retention capacity, which are important to characterise the actual water balance.

Apart from that, our analysis of the lag-effect showed that there can be drought-related mortality which did not occur in the designated IPDs, but in the following period. In the meta-analysis of Trugman et al. (2018), the majority of mortality occurred within the first ten years following a drought event, while in our analysis, most inventory periods in the experiments were shorter than a decade. This suggests that not all drought-related mortality might have been captured within the respective inventory period.

With the anticipated increasing frequency of droughts, it will become even harder to attribute mortality to one particular stress event. It will therefore become more important to account for the effect of multiyear or recurrent droughts on mortality (Sánchez-Pinillos et al. 2022). For instance, multiyear droughts were found to exacerbate mortality significantly, while three "wet" years following a drought mitigated it (Bradford et al. 2021). To improve our ability to relate mortality to a particular drought event, it would be necessary to monitor the condition of individual trees more closely. For example, mortality assessment in thinning experiments could be supplemented with data on annual radial increment to further elucidate the relation between drought stress and tree death. Interestingly, such studies that assessed both growth response and mortality consistently exhibited higher basal area increment and higher survival in heavily thinned treatments during and after drought, indicating a higher drought resistance and drought recovery of individual trees (Calev et al. 2016; Giuggiola et al. 2013; Knapp et al. 2021) and at the stand-level (Zhang et al. 2019). Likewise, comparative investigations of annual radial growth of trees deceased during droughts and survivors revealed that the deceased trees already had displayed lower radial growth in previous droughts (Cailleret et al. 2017; Dulamsuren et al. 2022), typically with lower drought resistance values in angiosperms and lower drought recovery values in gymnosperms (DeSoto et al. 2020). In addition to such a retrospective approach using radial increment, the response to drought and thinning could be monitored through repeated assessments of crown conditions, for example with unmanned aerial vehicles (Sankey & Tatum 2022), or ongoing measurement of growth using dendrometers (Aldea et al. 2023). One important step in this direction, which would add considerable value to existing thinning experiments, would be the assessment of tree conditions during and directly after severe or extreme drought impacts and not only following a prescribed inventory interval.

Further, the striking discrepancy between the initially large number of reported thinning studies and the small number of papers that could eventually be used in this meta-analysis on mortality calls for a different type of reporting in publications, so that these can be used in systematic reviews; an issue that has been identified also in relation to other ecological topics (e.g. Vetter et al. 2016). We would therefore like to encourage authors of future papers on thinning studies to: (a) report mortality in thinning experiments with a measure of variance, (b) clarify which mortality was actually measured (number of dead stems or proportion of dead basal area), (c) inform about the (major) causes of mortality, and (d) specify the exact time interval in which the mortality was measured. Also, documentation of soil water holding capacities would immensely help to correct for site effects and help overcome shortcomings of commonly used climatically based drought indices (Schwarz et al. 2020; Zang et al. 2020).

In scientific literature and practical manuals, thinning is frequently mentioned as one possible adaptation option to reduce drought stress. Yet, many forest professionals believe that the current level of knowledge to support its application for that purpose is limited (Himes et al. 2023). This calls for a better synthesis and communication of the results from the many thinning trials that exist all over the world. The results may be compiled in a global data base. Unfortunately, the subtropical and tropic regions seem to be under represented in published studies though (Sohn et al. 2016; Moreau et al. 2022). Despite the many thinning experiments reported in literature, it has been difficult to obtain data on tree mortality. This may have to do with the fact that the existing data are not curated and stored in a way that facilitates sharing.

A consequence of the diversity of studies included in this meta-analysis was the high variability. We view the broad coverage of regions as a strength for investigating the overall effect of thinning. Nevertheless, there is a trade-off between generalisability and comparability of study conditions. A geographic focus may provide insights into distinct regional thinning effects, when there are sufficient studies available. Likewise, the different studies employed a range of thinning methods. These different thinning methods, however, could not be included as an experimental factor but could only be addressed indirectly by looking at the consequences of exposure with the dominance index. The high variability that we, and many others encountered, could be reduced with substantially more studies comprising different forest types, tree species and varying thinning intensities, methods and intervals. These studies should then have a detailed reporting of growth/mortality assessments with causes of mortality and include results from replicate treatments to permit calculation of standard errors.

So far, most thinning experiments have been conducted in mono-specific stands. Since mixed-species forests also feature prominently among silvicultural approaches to adapt forests to global change (Messier et al. 2021), more studies that analyse thinning responses including mortality in mixed stands are urgently needed.

Lastly, results of thinning experiments that measure hydraulic variables such as soil moisture, tree water use or stomatal conductance (Breda et al., 1995; del Campo et al. 2022), leaf-level physiological processes (Minocha et al. 2013) or microclimatic effects (Menge et al. 2023) should be combined with mortality assessments to improve the understanding of processes behind drought-related mortality. Moreover, installing more rainfall exclusion roofs in thinning experiments (Cotillas et al. 2009; Pretzsch et al. 2014) offers the opportunity to investigate multiple year drought effects on tree mortality under controlled conditions.

5 Conclusion and management implications

In light of the pressing need for robust analysis amidst rapid changes and uncertainty, it is imperative that we emphasise comprehensive documentation of studies addressing adaptation options. By adhering to rigorous reporting standards and fostering the compilation of well-documented data, we can pave the way for more insightful analyses and informed decision-making, thus enhancing our collective capacity to address critical challenges in forest adaptation to climate change.

Conducting the first meta-analysis on thinning and drought-related mortality, we were challenged by the restricted database and a resultant high variability in the response of drought-related mortality to thinning. Even though thinning did not show a significant reduction in tree mortality following drought, one should not discard it as an option to increase the resistance of trees and stands against drought stress. We could show that the release through thinning does not lead to increased mortality of more dominant trees. Further exploration of how stand conditions (site, tree species, stand age, thinning intensity, etc.) influence the effects of thinning on reducing drought-related mortality would be worthwhile. In addition, thinning still offers many other benefits such as increased resistance and resilience in relation to other disturbances (Moreau et al. 2022), or facilitating important transformation processes, such as advance regeneration of more drought-adapted species (Millar et al. 2007).

Appendix

Table 3 Search strings for the search in Web of Science, the 5 strings are connected with the Boolean "AND"

Search string	Search terms
Forest string	forest* OR tree
Management string	thinning OR "stand density" OR "basal area reduction" OR "forest management" OR sylvicultur* OR silvicultur* OR "density reduction" OR "density treatment"
Mortality string	mortality OR "tree death" OR "dying trees" OR "vitality loss" OR dieback OR defoliat* OR "water stress"
Drought string	resilience OR drought OR "adaption capacity" OR adaptivity OR resistance
Exclusion string	NOT ALL=(mangrove* OR agroforestry OR amazon* OR borer OR nematode) NOT TI = ("budworm" OR beetle* OR moth OR canker OR fuel OR fire OR wildfire OR seedling OR fung* OR pest OR infect*

The asterisk (*) is used as a truncation symbol to include different word endings, such as 'fung*' to capture 'fungi', 'fungal', etc.

Table 4 2 × 2 contingency table for risk ratio calculation

	Thinned	Control
Dead	A	B
Alive	C	D
Total	N1	N2

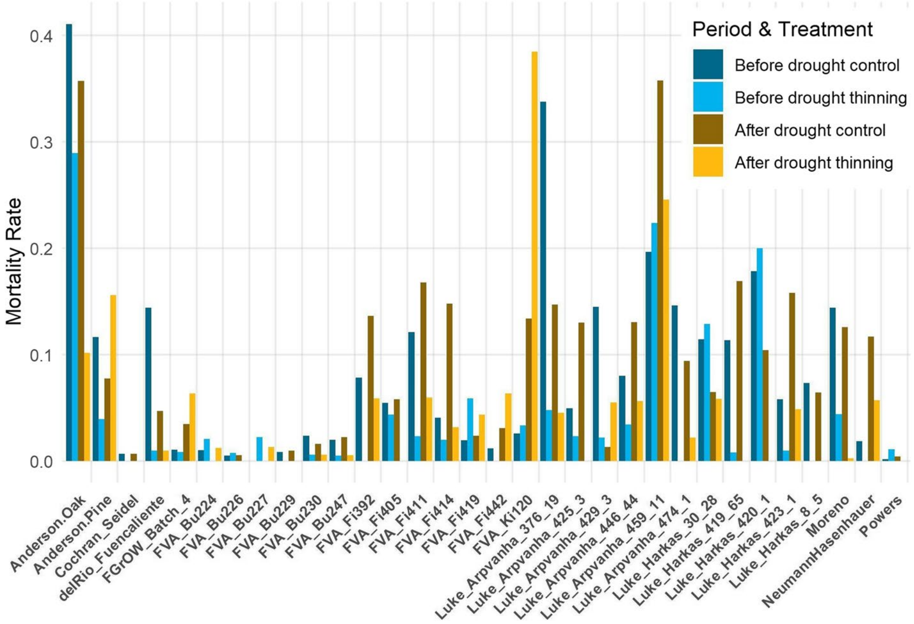

Fig. 10 Mortality rates of the experiments by treatment in the inventory period before and with drought. The mortality rate is the number of dead stems per site divided by the total number of stems per site

Table 5 Subgroup analysis and meta-regressions statistics of pre-drought and IPD

				Pre-drought inventory period						**Drought inventory period**					
Covariate	**Var type**	**Coef type**	**N**	**Coef**	**CI.lb**	**CI.ub**	**p**	**SL**	**R^2**	**Coef**	**CI.lb**	**CI.ub**	**p**	**SL**	**R^2**
Koeppen-ClimateZone	cl.	Warm/arid	2	0.16	0.03	0.71	0.016	*	0	0.08	0.01	0.54	0.01	**	11.3
Koeppen-ClimateZone	cl.	Temperate	3	0.64	0.13	3.18	0.582		0	1.2	0.27	5.75	0.783		11.3
Koeppen-ClimateZone	cl.	Continental	27	0.45	0.28	0.73	0.001	**	0	0.44	0.26	0.74	0.002	**	11.3
Taxonomic-Class	cl.	Mixed	1	0.79	0.04	16.40	0.878		0	1.82	0.14	23.07	0.644		0
Taxonomic-Class	cl.	Conifers	22	0.62	0.24	1.61	0.325		0	0.36	0.12	1.06	0.064	.	0
Taxonomic-Class	cl.	Broad leaves	9	0.37	0.22	0.62	0	***	0	0.42	0.23	0.76	0.004	**	0
Genus	cl.	*Fagus*	6	0.77	0.20	2.93	0.704		0	0.69	0.15	3.14	0.63		0
Genus	cl.	*Larix*	1	0.85	0.02	29.6	0.929		0	0.85	0.02	37.62	0.931		0
Genus	cl.	*Picea*	11	0.50	0.24	1.04	0.063	.	0	0.28	0.12	0.67	0.005	**	0
Genus	cl.	*Pinus*	10	0.27	0.13	0.56	0	***	0	0.58	0.25	1.34	0.203		0
Genus	cl.	*Populus*	1	0.79	0.04	16.35	0.878		0	1.82	0.14	24.08	0.649		0
Genus	cl.	*Quercus*	3	0.49	0.13	1.92	0.308		0	0.17	0.03	0.85	0.031	*	0
Latitude	co.	Interc	32	1.54	0.10	22.98	0.755		0	1.78	0.07	46.92	0.731		0
Latitude	co.	Coef		0.98	0.93	1.03	0.344		0	0.97	0.92	1.04	0.386		0
Stand-Density	co.	Interc	32	0.21	0.06	0.69	0.01	*	4.1	0.18	0.05	0.66	0.01	*	0
Stand-Density	co.	Coef		3.70	0.47	28.81	0.212		4.1	4.48	0.57	35.58	0.156		0

Table 5 (continued)

Covariate	Var type	Coef type	N	Pre-drought inventory period						Drought inventory period					
				Coef	CI.lb	CI.ub	p	SL	R^2	Coef	CI.lb	CI.ub	p	SL	R^2
TreeAge	co.	Interc	32	0.52	0.15	1.80	0.302		0	0.17	0.04	0.78	0.022	*	0
TreeAge	co.	Coef		1.00	0.98	1.01	0.731		0	1.01	0.99	1.03	0.206		0
Timesince-lastThin	co.	Interc	32	0.48	0.23	0.981	0.044	*	0	0.29	0.13	0.65	0.002	**	3.0
Timesince-lastThin	co.	Coef		0.99	0.94	1.036	0.608		0	1.02	0.98	1.06	0.312		3.0

Var type Variable type, *cl*. class, *co*. continuous, *Coef type* coefficient type, *interc*. intercept, *coef* coefficient, *N* number of experiments within subgroup/regression, *CI. lb* confidence interval lower boundary, *CI.ub* confidence interval upper boundary, *p p* -value, *SL* significance level, R^2 amount of heterogeneity that can be explain by covariates

Significant levels used were $p < 0.05$ = *, $p < 0.01$ = **, $p < 0.001$ = ***

Table 6 Table of Dominance Index and average diameter table (in m) and age at the start of the IPB in years; dominance indices are unitless

		Dominance Index				*Average Diameter (derived from basal area)*							
		Pre-drought		Drought		Pre-drought				Drought			
Study	Age	Control	Thinned	Control	Thinned	Control alive	Control dead	Thinned alive	Thinned dead	Control alive	Control dead	Thinned alive	Thinned dead
Harkas_30_28_2011	62	1.835	2.368	1.875	2.656	0.157	0.116	0.176	0.114	0.193	0.141	0.216	0.132
Arpvanha_376_19_2015	107	2.487	1.7	2.076	2.042	0.151	0.096	0.213	0.164	0.172	0.12	0.231	0.162
Arpvanha_429_3_2014	123	2.096	1.098	1.33	0.959	0.214	0.148	0.293	0.279	0.209	0.181	0.302	0.308
Arpvanha_446_44_2012	124	1.477	3.106	1.392	1.913	0.271	0.223	0.313	0.178	0.29	0.246	0.338	0.245
Arpvanha_459_11_2019	67	2.555	1.369	1.703	1.518	0.19	0.119	0.239	0.204	0.224	0.172	0.285	0.231
FVA_Bu230_2004	116	5.036	2.482	4.47	6.141	0.316	0.141	0.328	0.208	0.334	0.158	0.344	0.139
FVA_Fi411_2018	66	2.451	4.042	1.652	2.06	0.264	0.169	0.381	0.19	0.287	0.224	0.405	0.282
FVA_Fi414_2008	53	3.281	1.452	3.091	2.265	0.225	0.124	0.303	0.251	0.242	0.138	0.337	0.224
FVA_Fi419_2017	55	9.996	1.459	9.075	1.164	0.276	0.087	0.332	0.275	0.307	0.102	0.359	0.332
Harkas_419_65_2011	49	2.666	1.806	2.1	2.056	0.158	0.097	0.201	0.15	0.18	0.124	0.224	0.156
NeumannHasen-hauer_2019	105	1.909	1.507	2.089	2.129	0.181	0.131	0.244	0.198	0.179	0.124	0.261	0.179
delRio_Fuencaliente_2015	59	1.638	1.289	1.491	1.882	0.17	0.133	0.206	0.182	0.182	0.149	0.215	0.157
Harkas_423_1_2010	76	2.162	1.881	1.727	1.641	0.201	0.137	0.254	0.185	0.214	0.163	0.27	0.21
FGrOW_Batch_4_2021	25	0.984	0.903	1.429	1.207	0.101	0.102	0.1	0.105	0.112	0.094	0.113	0.103
FVA_Ki120_2019	54	2.088	1.282	0.94	1.084	0.262	0.181	0.277	0.244	0.279	0.287	0.292	0.281
Mean	**75**	**3.122**	**3.429**	**2.356**	**2.37**	**0.21**	**0.131**	**0.257**	**0.186**	**0.227**	**0.164**	**0.279**	**0.203**

Analysis of lagged tree mortality

The dataset used for analysing the lag effect of mortality after drought consisted only of 12 experiments because in most experiments the inventory period that followed IPD included either another drought event, or the data was simply not available. Therefore, the explanatory power of our results is constrained. The calculated risk ratio for IPA was lower than in IPB and higher than in IPD (Appendix Fig. 11). The values of all periods clearly fall below 1; however, they are not significantly different from each other as can be seen by the overlapping confidence intervals (Appendix Fig. 11). The meta-analyses for the three periods also exhibited rather high heterogeneity (I^2>60%). Owing to the low number of samples per genera, a more detailed subgroup analysis of the interaction between the genus of the main species combined with the lag effect was not meaningful.

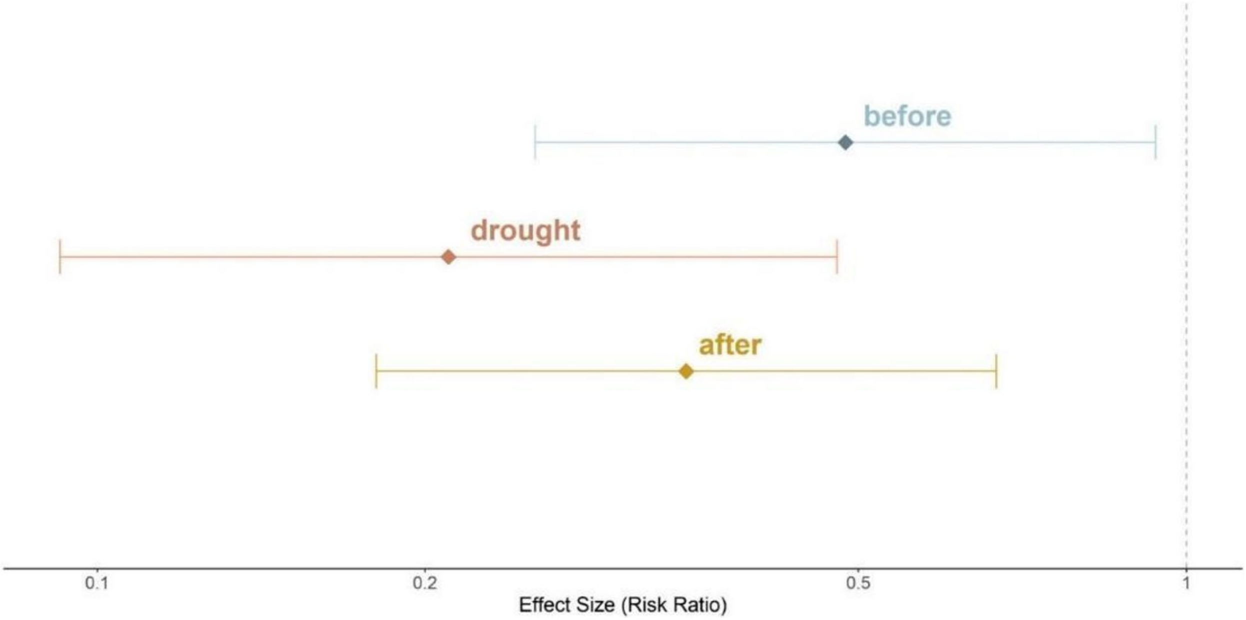

Fig. 11 Forest plot of meta-analysis with before (blue), during (red) and after (yellow) drought period, *x*-axis is in log scale, the lower the effect size the lower is the mortality rate in thinned stands relative to their control. Analysis was conducted with a subsample of studies (12) for which an inventory period after the period in which the drought occured was available

Acknowledgements
We would like to express our sincere gratitude to the Forest Growth Organization of Western Canada, the Natural Resource Institute Finland Luke, the Forest Research Institute Baden-Württemberg, the Ecological and Forestry Applications Research Centre, CREAF, Cerdanyola del Vallès and the Department of Forest Dynamics and Management, Instituto de Ciencias Forestales (ICIFOR-INIA), CSIC for their invaluable data contribution. Further, we would like to thank Mathias Neumann of University of Natural Resources and Life Sciences, Vienna for his contribution of additional data to the publication Neumann and Hasenauer (2021); Benjamin O. Knapp of the University Missouri for his contribution of additional data to the thesis of Samantha Anderson (Anderson, 2017); Yagil Osem of the Institute of Plant sciences, Bet Dagan for his contribution of additional data to the publication Calev et al. (2016); Daniel Moreno Fernández of the Technical University Madrid for his contribution of additional data to the publication Moreno Fernández et al. (2021).

Code availability
The custom code generated during and/or analysed during the current study are not publicly available as it contains data with restricted availability but are available from the corresponding author on reasonable request.

Authors' contributions
The concept for the article was developed by Julius Willig, Julia Schwarz and Jürgen Bauhus. The literature search and data analysis was performed by Julius Willig with the help of Julia Schwarz. Philip Comeau, Ulrich Kohnle, Josep Maria Espelta, Harri Mäkinen, Roma Ogaya, Mikko Peltoniemi, Josep Penuelas, Brian Roth, Ricardo Ruiz-Peinado and Florian Ruge contributed with data and/or data curation. Julius Willig wrote the first draft of the manuscript. Jürgen Bauhus, Philip Comeau, Henrik Hartmann, Ulrich Kohnle, Josep Maria Espelta, Harri Mäkinen, Roma Ogaya, Mikko Peltoniemi, Josep Penuelas, Brian Roth, Ricardo Ruiz-Peinado, Florian Ruge and Julia Schwarz commented on previous versions of the manuscript. Jürgen Bauhus supervised the study. The authors read and approved the final manuscript.

Funding
Open Access funding enabled and organized by Projekt DEAL. The research was supported by the RESONATE Project funded by the European Union's Horizon 2020 research and innovation programme under grant agreement number 101000574. Mäkinen has received funding from the European Union—NextGenerationEU instrument and is funded by the Research Council of Finland under grant number 347782.

Data availability
The data that support the findings of this study are available from the authors but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of the respective organisations.

Declarations

Consent for publication
All authors gave their informed consent to this publication and its content.

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Institute of Forest Sciences, Chair of Silviculture, University of Freiburg, Stefan-Meier-Straße 76, Freiburg 79104, Germany. [2]Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Zürcherstraße 111, 8903 Birmensdorf, Switzerland. [3]Department of Renewable Resources Department, University of Alberta, 751 General Services Building, Edmonton, AB, Canada. [4]Institute for Forest Protection, Julius Kühn Institute (JKI) -Federal Research Centre for Cultivated Plants, Erwin-Baur-Straße 27, 06484 Quedlinburg, Germany. [5]Faculty of Forest Sciences and Forest Ecology, Georg-August-University Göttingen, Büsgenweg 5, 37077 Göttingen, Germany. [6]Forest Research

Institute Baden-Württemberg, Wonnhaldestraße 4, 79100 Freiburg, Germany. [7]CREAF, Bellaterra (Cerdanyola del Vallès), Catalonia E08193, Spain. [8]Universitat Autònoma de Barcelona, Plaça Cívica, Bellaterra, Barcelona, Catalonia, Spain. [9]Luke Natural Resource Institute Finland, Latokartanonkaari 9, 00790 Helsinki, Finland. [10]CSIC, Global Ecology Unit CREAF-CSIC-UAB, 08193 Bellaterra, Catalonia, Spain. [11]Forest Release, Somerville, ME, USA. [12]Instituto de Ciencias Forestales (ICIFOR-INIA), CSIC, Ctra. de La Coruña, Km. 7.5, 28040 Madrid, Spain.

Received: 19 April 2024 Accepted: 22 January 2025

References

Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A., & Hegewisch, K. C. (2018). TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. Scientific Data, 5(1), Article 1. https://doi.org/10.1038/sdata.2017.191

Agnew, C. T. (2000). Using the SPI to Identify Drought. Drought Network News (1994–2001). https://digitalcommons.unl.edu/droughtnetnews/1

Aldea J, del Río M, Cattaneo N, Riofrío J, Ordóñez C, Uzquiano S, Bravo F (2023) Short-term effect of thinning on inter- and intra-annual radial increment in Mediterranean Scots pine-oak mixed forests. For Ecol Manage 549:121462. https://doi.org/10.1016/j.foreco.2023.121462

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg EH, (Ted), Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S. W., Semerci, A., & Cobb, N. (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manage 259(4):660–684. https://doi.org/10.1016/j.foreco.2009.09.001

Allen, C. D., Breshears, D. D., & McDowell, N. G. (2015). On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere, 6(8), art129. https://doi.org/10.1890/ES15-00203.1

Anderegg WRL, Kane JM, Anderegg LDL (2013) Consequences of widespread tree mortality triggered by drought and temperature stress. Nat Clim Chang 3(1):30–36. https://doi.org/10.1038/nclimate1635

Anderegg WRL, Hicke JA, Fisher RA, Allen CD, Aukema J, Bentz B, Hood S, Lichstein JW, Macalady AK, McDowell N, Pan Y, Raffa K, Sala A, Shaw JD, Stephenson NL, Tague C, Zeppel M (2015) Tree mortality from drought, insects, and their interactions in a changing climate. New Phytol 208(3):674–683. https://doi.org/10.1111/nph.13477

Anderson, S. E. (2017). Effects of stand density on mitigation and adaptability to climate change in pine and hardwood forests of Missouri [Thesis, University of Missouri--Columbia]. https://doi.org/10.32469/10355/65963

Bauhus, J., Dieter, M., Farwig, N., Hafner, A., Kätzel, R., Kleinschmit, B., Lang, F., Lindner, M., Möhring, B., Müller, J., Niekisch, M., Richter, K., Schraml, U., & Seeling, U. (2021). Die Anpassung von Wäldern und Waldwirtschaft an den Klimawandel: Gutachten des Wissenschaftlichen Beirates für Waldpolitik. Bundesministerium für Ernährung und Landwirtschaft.

Bennett, A. C., McDowell, N. G., Allen, C. D., & Anderson-Teixeira, K. J. (2015). Larger trees suffer most during drought in forests worldwide. Nature Plants, 1(10), Article 10. https://doi.org/10.1038/nplants.2015.139

Bigler C, Gavin DG, Gunning C, Veblen TT (2007) Drought induces lagged tree mortality in a subalpine forest in the Rocky Mountains. Oikos (Copenhagen, Denmark) 116(12):1983–1994

Bjelanovic I, Comeau P, Meredith S, Roth B (2021) Precommercial Thinning Increases Spruce Yields in Boreal Mixedwoods in Alberta. Canada Forests 12(4):412. https://doi.org/10.3390/f12040412

Bolte A, Ammer C, Löf M, Madsen P, Nabuurs G-J, Schall P, Spathelf P, Rock J (2009) Adaptive forest management in central Europe: Climate change impacts, strategies and integrative concept. Scand J for Res 24(6):473–482. https://doi.org/10.1080/02827580903418224

Borenstein, M., Hedges, L. V., Higgins, J. P. T., & Rothstein, H. R. (2009). Introduction to Meta-Analysis (1st ed.). Wiley. https://doi.org/10.1002/9780470743386

Bosela M, Štefančík I, Marčiš P, Rubio-Cuadrado Á, Lukac M (2021) Thinning decreases above-ground biomass increment in central European beech forests but does not change individual tree resistance to climate events. Agric for Meteorol 306:108441. https://doi.org/10.1016/j.agrformet.2021.108441

Bottero A, D'Amato AW, Palik BJ, Bradford JB, Fraver S, Battaglia MA, Asherin LA (2017) Density-dependent vulnerability of forest ecosystems to drought. J Appl Ecol 54(6):1605–1614. https://doi.org/10.1111/1365-2664.12847

Bottero A, Forrester DI, Cailleret M, Kohnle U, Gessler A, Michel D, Bose AK, Bauhus J, Bugmann H, Cuntz M, Gillerot L, Hanewinkel M, Lévesque M, Ryder J, Sainte-Marie J, Schwarz J, Yousefpour R, Zamora-Pereira JC, Rigling A (2021) Growth resistance and resilience of mixed silver fir and Norway spruce forests in central Europe: Contrasting responses to mild and severe droughts. Glob Change Biol 27(18):4403–4419. https://doi.org/10.1111/gcb.15737

Bradford J, B., Shriver, R. K., Robles, M. D., McCauley, L. A., Woolley, T. J., Andrews, C. A., Crimmins, M., & Bell, D. M. (2021) Tree mortality response to drought-density interactions suggests opportunities to enhance drought resistance. J Appl Ecol 1365–2664:14073. https://doi.org/10.1111/1365-2664.14073

Bréda, N., Granier, A., & Aussenac, G. (1995). Effects of thinning on soil and tree water relations, transpiration and growth in an oak forest (*Quercus petraea* (Matt.) Liebl.). Tree Physiology, 15(5), 295–306. https://doi.org/10.1093/treephys/15.5.295

Brooks JR, Mitchell AK (2011) Interpreting tree responses to thinning and fertilization using tree-ring stable isotopes. New Phytol 190(3):770–782. https://doi.org/10.1111/j.1469-8137.2010.03627.x

Bucher D, Bauhus J, Kohnle U (2023) Beeinflusst die Waldbewirtschaftung die Mortalität der Buche? Allgemeine Forstzeitschrift / der Wald 78:39–41

Cailleret, M., Jansen, S., Robert, E. M. R., Desoto, L., Aakala, T., Antos, J. A., Beikircher, B., Bigler, C., Bugmann, H., Caccianiga, M., Čada, V., Camarero, J. J., Cherubini, P., Cochard, H., Coyea, M. R., Čufar, K., Das, A. J., Davi, H., Delzon, S., … Martínez-Vilalta, J. (2017). A synthesis of radial growth patterns preceding tree mortality. Global Change Biology, 23(4), 1675–1690. https://doi.org/10.1111/gcb.13535

Calev A, Zoref C, Tzukerman M, Moshe Y, Zangy E, Osem Y (2016) High-intensity thinning treatments in mature *Pinus halepensis* plantations experiencing prolonged drought. Eur J Forest Res 135(3):551–563. https://doi.org/10.1007/s10342-016-0954-y

Callahan, R. P., Riebe, C. S., Sklar, L. S., Pasquet, S., Ferrier, K. L., Hahm, W. J., Taylor, N. J., Grana, D., Flinchum, B. A., Hayes, J. L., & Holbrook, W. S. (2022). Forest vulnerability to drought controlled by bedrock composition. Nature Geoscience, 15(9), Article 9. https://doi.org/10.1038/s41561-022-01012-2

Cantarello E, Newton AC, Martin PA, Evans PM, Gosal A, Lucash MS (2017) Quantifying resilience of multiple ecosystem services and biodiversity in a temperate forest landscape. Ecol Evol 7(22):96619675. https://doi.org/10.1002/ece3.3491

Castagneri, D., Vacchiano, G., Hacket-Pain, A., DeRose, R. J., Klein, T., & Bottero, A. (2021). Meta-analysis Reveals Different Competition Effects on Tree Growth Resistance and Resilience to Drought. Ecosystems 25, 30–43 (2022). https://doi.org/10.1007/s10021-021-00638-4

Cochran PH, Seidel KW (1999) Growth and yield of western larch under controlled levels of stocking in the Blue Mountains of Oregon. USDA Forest Service Pacific Northwest Research Station Research Paper, p 517, 1-+

Cotillas M, Sabaté S, Gracia C, Espelta JM (2009) Growth response of mixed mediterranean oak coppices to rainfall reduction: Could selective thinning have any influence on it? For Ecol Manage 258(7):1677–1683. https://doi.org/10.1016/j.foreco.2009.07.033

D'Amato AW, Bradford JB, Fraver S, Palik BJ (2013) Effects of thinning on drought vulnerability and climate response in north temperate forest ecosystems. Ecol Appl 23(8):1735–1742. https://doi.org/10.1890/13-0677.1

del Campo AD, Otsuki K, Serengil Y, Blanco JA, Yousefpour R, Wei X (2022) A global synthesis on the effects of thinning on hydrological processes: Implications for forest management. For Ecol Manage 519:120324. https://doi.org/10.1016/j.foreco.2022.120324

DeSoto, L., Cailleret, M., Sterck, F., Jansen, S., Kramer, K., Robert, E. M. R., Aakala, T., Amoroso, M. M., Bigler, C., Camarero, J. J., Čufar, K., Gea-Izquierdo, G., Gillner, S., Haavik, L. J., Hereş, A.-M., Kane, J. M., Kharuk, V. I., Kitzberger, T., Klein, T., … Martínez-Vilalta, J. (2020). Low growth resilience to drought is related to future mortality risk in trees. Nature Communications, 11(1), 545. https://doi.org/10.1038/s41467-020-14300-5

Dulamsuren C, Bat-Enerel B, Meyer P, Leuschner C (2022) Did stand opening 60 years ago predispose a European beech population to death? Trees. Forests and People 8:100265. https://doi.org/10.1016/j.tfp.2022.100265

Elicit. (2022). *Elicit: The AI Research Assistant*. Retrieved from https://elicit.com

Fernández-de-Uña L, Martínez-Vilalta J, Poyatos R, Mencuccini M, McDowell NG (2023) The role of height-driven constraints and compensations on tree vulnerability to drought. New Phytol 239(6):2083–2098. https://doi.org/10.1111/nph.19130

Fleiss JL, Berlin JA (2009) Effect sizes for dichotomous data. The Handbook of Research Synthesis and Meta-Analysis 2:237–253

Garber S, Lam TY, Maguire DA (2011) Growth and Mortality of Residual Douglas-Fir after Regeneration Harvests under Group Selection and Two-Story Silvicultural Systems. West J Appl for 26(2):64–70. https://doi.org/10.1093/wjaf/26.2.64

Gebhardt T, Häberle K-H, Matyssek R, Schulz C, Ammer C (2014) The more, the better? Water relations of Norway spruce stands after progressive thinning. Agric for Meteorol 197:235–243. https://doi.org/10.1016/j.agrformet.2014.05.013

George J-P, Bürkner P-C, Sanders TGM, Neumann M, Cammalleri C, Vogt JV, Lang M (2022) Long-term forest monitoring reveals constant mortality rise in European forests. Plant Biol 24(7):1108–1119. https://doi.org/10.1111/plb.13469

Giuggiola A, Bugmann H, Zingg A, Dobbertin M, Rigling A (2013) Reduction of stand density increases drought resistance in xeric Scots pine forests. For Ecol Manage 310:827–835. https://doi.org/10.1016/j.foreco.2013.09.030

Gleason, K. E., Bradford, J. B., Bottero, A., D'Amato, A. W., Fraver, S., Palik, B. J., Battaglia, M. A., Iverson, L., Kenefic, L., & Kern, C. C. (2017). Competition amplifies drought stress in forests across broad climatic and compositional gradients. Ecosphere, 8(7). https://doi.org/10.1002/ecs2.1849

Guillemot J, Klein EK, Davi H, Courbet F (2015) The effects of thinning intensity and tree size on the growth response to annual climate in *Cedrus atlantica*: A linear mixed modeling approach. Ann for Sci 72(5):651–663. https://doi.org/10.1007/s13595-015-0464-y

Hammond, W. M., Williams, A. P., Abatzoglou, J. T., Adams, H. D., Klein, T., López, R., Sáenz-Romero, C., Hartmann, H., Breshears, D. D., & Allen, C. D. (2022). Global field observations of tree die-off reveal hotter-drought fingerprint for Earth's forests. Nature Communications, 13(1), Article 1. https://doi.org/10.1038/s41467-022-29289-2

Harrer, M., Cuijpers, P., A, F. T., & Ebert, D. D. (2021). Doing meta-analysis with R: A hands-on guide (1st ed.). Chapman & Hall/CRC Press.

Hartmann, H., Moura, C. F., Anderegg, W. R. L., Ruehr, N. K., Salmon, Y., Allen, C. D., Arndt, S. K., Breshears, D. D., Davi, H., Galbraith, D., Ruthrof, K. X., Wunder, J., Adams, H. D., Bloemen, J., Cailleret, M., Cobb, R., Gessler, A., Grams, T. E. E., Jansen, S., … O'Brien, M. (2018). Research frontiers for improving our understanding of drought-induced tree and forest mortality. New Phytologist, 218(1), 15–28. https://doi.org/10.1111/nph.15048

Hartmann H, Bastos A, Das AJ, Esquivel-Muelbert A, Hammond WM, Martínez-Vilalta J, McDowell NG, Powers JS, Pugh TAM, Ruthrof KX, Allen CD (2022) Climate Change Risks to Global Forest Health: Emergence of Unexpected Events of Elevated Tree Mortality Worldwide. Annu Rev Plant Biol 73(1):673–702. https://doi.org/10.1146/annurev-arplant-102820-012804

He Q, Bertness MD, Altieri AH (2013) Global shifts towards positive species interactions with increasing environmental stress. Ecol Lett 16(5):695–706. https://doi.org/10.1111/ele.12080

Higgins JPT, Thompson SG (2002) Quantifying heterogeneity in a meta-analysis. Stat Med 21(11):1539–1558. https://doi.org/10.1002/sim.1186

Higgins JPT, Thompson SG (2004) Controlling the risk of spurious findings from meta-regression. Stat Med 23(11):1663–1682. https://doi.org/10.1002/sim.1752

Higgins, J. P. T., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M., & Welch, V. (2019). Cochrane Handbook for Systematic Reviews of Interventions. Wiley-Blackwell. https://research.monash.edu/en/publications/cochrane-handbook-for-systematic-reviews-of-interventions

Hilmers T, Schmied G, Pretzsch H (2022) Legacy effects of past thinnings modulate drought stress reactions at present Scand J Forest Res 37(3):182–199. https://doi.org/10.1080/02827581.2022.2096920

Himes, A., Bauhus, J., Adhikari, S., Barik, S. K., Brown, H., Brunner, A., Burton, P. J., Coll, L., D'Amato, A. W., Diaci, J., Dorji, Y., Foli, E. G., Ganz, D. J., Hall, J. S., Keenan, R., Lu, Y., Messier, C., Munanura, I., Piotto, D., … Puettmann, K. J. (2023). Forestry in the Face of Global Change: Results of a Global Survey of Professionals. Current Forestry Reports. https://doi.org/10.1007/s40725-023-00205-1

Hyatt LA, Rosenberg MS, Howard TG, Bole G, Fang W, Anastasia J, Brown K, Grella R, Hinman K, Kurdziel JP, Gurevitch J (2003) The distance dependence prediction of the Janzen-Connell hypothesis: A meta-analysis. Oikos 103(3):590–602. https://doi.org/10.1034/j.1600-0706.2003.12235.x

Jump AS, Ruiz-Benito P, Greenwood S, Allen CD, Kitzberger T, Fensham R, Martínez-Vilalta J, Lloret F (2017) Structural overshoot of tree growth with climate variability and the global spectrum of drought-induced forest dieback. Glob Change Biol 23(9):3742–3757. https://doi.org/10.1111/gcb.13636

Klein T (2020) A race to the unknown: Contemporary research on tree and forest drought resistance, an Israeli perspective. J Arid Environ 172:104045. https://doi.org/10.1016/j.jaridenv.2019.104045

Klesse S, Wohlgemuth T, Meusburger K, Vitasse Y, von Arx G, Lévesque M, Neycken A, Braun S, Dubach V, Gessler A, Ginzler C, Gossner MM, Hagedorn F, Queloz V, Samblás Vives E, Rigling A, Frei ER (2022) Long-term soil water limitation and previous tree vigor drive local variability of drought-induced crown dieback in *Fagus sylvatica*. Sci Total Environ 851:157926. https://doi.org/10.1016/j.scitotenv.2022.157926

Knapp EE, Bernal AA, Kane JM, Fettig CJ, North MP (2021) Variable thinning and prescribed fire influence tree mortality and growth during and after a severe drought. For Ecol Manage 479:118595. https://doi.org/10.1016/j.foreco.2020.118595

Koricheva J, Gurevitch J (2014) Uses and misuses of meta-analysis in plant ecology. J Ecol 102(4):828–844. https://doi.org/10.1111/1365-2745.12224

Kulha N, Honkaniemi J, Barrere J, Brandl S, Cordonnier T, Korhonen KT, Kunstler G, Paul C, Reineking B, Peltoniemi M (2023) Competition-induced tree mortality across Europe is driven by shade tolerance, proportion of conspecifics and drought. J Ecol 111(10):2310–2323. https://doi.org/10.1111/1365-2745.14184

Lindner M, Fitzgerald JB, Zimmermann NE, Reyer C, Delzon S, van der Maaten E, Schelhaas M-J, Lasch P, Eggers J, van der Maaten-Theunissen M, Suckow F, Psomas A, Poulter B, Hanewinkel M (2014) Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management? J Environ Manage 146:69–83. https://doi.org/10.1016/j.jenvman.2014.07.030

Lindner, M., Nikinmaa, L., Brang, P., Cantarello, E., & Seidl, R. (2020). Enhancing Resilience to Address Challenges in Forest Management.

Lopez B, Sabate S, Gracia C (1998) Fine roots dynamics in a Mediterranean forest: Effects of drought and stem density. Tree Physiol 18(8–9):601–606

Lucas-Borja, M. E., Bose, A. K., Andivia, E., Candel-Pérez, D., Plaza-Álvarez, P. A., & Linares, J. C. (2021). Assessing Tree Drought Resistance and Climate-Growth Relationships under Different Tree Age Classes in a *Pinus nigra Arn. Ssp. Salzmannii* Forest. Forests, 12(9), Article 9. https://doi.org/10.3390/f12091161

Mäkinen, H., & Isomäki, A. (2004). Thinning intensity and growth of Norway spruce stands in Finland. Forestry: An International Journal of Forest Research, 77(4), 349–364. https://doi.org/10.1093/forestry/77.4.349

Mason, B., & Valinger, E. (2013). Managing forests to reduce storm damage. In B. Gardiner, A. Schuck, M.-J. Schelhaas, C. Orazio, K. Blennow, & B. Nicoll, Living with Storm Damage to Forests: What Science Can Tell Us (pp. 89–98). European Forest Institute, Joensuu, Finland.

McDowell NG, Pockman WT, Allen CD, Breshears DD, Cobb N, Kolb T, Plaut J, Sperry J, West A, Williams DG, Yepez EA (2008) Mechanisms of plant survival and mortality during drought: Why do some plants survive while others succumb to drought? New Phytol 178(4):719739. https://doi.org/10.1111/j.1469-8137.2008.02436.x

Menge JH, Magdon P, Woellauer S, Ehbrecht M (2023) Impacts of forest management on stand and landscape-level microclimate heterogeneity of European beech forests. Landscape Ecol 38(4):903–917. https://doi.org/10.1007/s10980-023-01596-z

Messier, C., Bauhus, J., Sousa-Silva, R., Auge, H., Baeten, L., Barsoum, N., Bruelheide, H., Caldwell, B., Cavender-Bares, J., Dhiedt, E., Eisenhauer, N., Ganade, G., Gravel, D., Guillemot, J., Hall, J. S., Hector, A., Hérault, B., Jactel, H., Koricheva, J., … Zemp, D. C. (2021). For the sake of resilience and multifunctionality, let's diversify planted forests! Conservation Letters. https://doi.org/10.1111/conl.12829

Meyer, P., Spînu, A. P., Mölder, A., & Bauhus, J. (2022). Management alters drought-induced mortality patterns in European beech (*Fagus sylvatica*

L.) forests. Plant Biology, 24(7), 1157–1170. https://doi.org/10.1111/plb.13396

Millar CI, Stephenson NL, Stephens SL (2007) Climate Change and Forests of the Future: Managing in the Face of Uncertainty. Ecol Appl 17(8):2145–2151. https://doi.org/10.1890/06-1715.1

Minocha R, Turlapati SA, Long S. et al. (2013) Fuel treatment effects on soil chemistry and foliar physiology of three coniferous species at the Teakettle Experimental Forest, California, USA. Trees 27:1101–1113. https://doi.org/10.1007/s00468-013-0860-6

Monserud R, Ledermann T, Sterba H (2004) Are self-thinning constraints needed in a tree-specific mortality model? Forest Science 50(6):848–858

Moreau G, Chagnon C, Achim A, Caspersen J, D'Orangeville L, Sánchez-Pinillos M, Thiffault N (2022) Opportunities and limitations of thinning to increase resistance and resilience of trees and forests to global change. Forestry, cpac010. https://doi.org/10.1093/forestry/cpac010

Moreno Fernández, D., Aldea, J., Gea-Izquierdo, G., Cañellas, I., & Martín-Benito, D. (2021). Influence of climate and thinning on *Quercus pyrenaica* Willd. Coppices growth dynamics. European Journal of Forest Research, 140(1), 187–197. https://doi.org/10.1007/s10342-020-01322-3

Neumann M, Hasenauer H (2021) Thinning Response and Potential Basal Area—A Case Study in a Mixed Sub-Humid Low-Elevation Oak-Hornbeam Forest. Forests 12(10):1354. https://doi.org/10.3390/f12101354

Neumann M, Mues V, Moreno A, Hasenauer H, Seidl R (2017) Climate variability drives recent tree mortality in Europe. Glob Change Biol 23(11):4788–4797. https://doi.org/10.1111/gcb.13724

Ogaya R, Escola A, Liu D, Barbeta A, Penuelas J (2020) Effects Of Thinning In a Water-Limited Holm Oak Forest. J Sustain for 39(4):365–378. https://doi.org/10.1080/10549811.2019.1673179

Powers MD, Palik BJ, Bradford JB, Fraver S, Webster CR (2010) Thinning method and intensity influence long-term mortality trends in a red pine forest. For Ecol Manage 260(7):1138–1148. https://doi.org/10.1016/j.foreco.2010.07.002

Pretzsch, H., Rötzer, T., Matyssek, R., Grams, T. E. E., Häberle, K.-H., Pritsch, K., Kerner, R., & Munch, J.-C. (2014). Mixed Norway spruce (*Picea abies* [L.] Karst) and European beech (*Fagus sylvatica* [L.]) stands under drought: From reaction pattern to mechanism. Trees, 28(5), 1305–1321. https://doi.org/10.1007/s00468-014-1035-9

R Core Team. (2022). R: A language and environment for statistical computing [Manual]. https://www.R-project.org/

Reineke, L. H. (1933). Perfecting a stand-density index for even- aged forests.

Sánchez-Pinillos M, D'Orangeville L, Boulanger Y, Comeau P, Wang J, Taylor AR, Kneeshaw D (2022) Sequential droughts: A silent trigger of boreal forest mortality. Glob Change Biol 28(2):542–556. https://doi.org/10.1111/gcb.15913

Sankey, T., & Tatum, J. (2022). Thinning increases forest resiliency during unprecedented drought. Scientific Reports, 12(1), Article 1. https://doi.org/10.1038/s41598-022-12982-z

Schmitt A, Trouvé R, Seynave I, Lebourgeois F (2020) Decreasing stand density favors resistance, resilience, and recovery of *Quercus petraea* trees to a severe drought, particularly on dry sites. Ann for Sci 77(2):52. https://doi.org/10.1007/s13595-020-00959-9

Schuldt, B., Buras, A., Arend, M., Vitasse, Y., Beierkuhnlein, C., Damm, A., Gharun, M., Grams, T. E. E., Hauck, M., Hajek, P., Hartmann, H., Hiltbrunner, E., Hoch, G., Holloway-Phillips, M., Körner, C., Larysch, E., Lübbe, T., Nelson, D. B., Rammig, A., … Kahmen, A. (2020). A first assessment of the impact of the extreme 2018 summer drought on Central European forests. Basic and Applied Ecology, 45, 86–103. https://doi.org/10.1016/j.baae.2020.04.003

Schwarz J, Skiadaresis G, Kohler M, Kunz J, Schnabel F, Vitali V, Bauhus J (2020) Quantifying Growth Responses of Trees to Drought—A Critique of Commonly Used Resilience Indices and Recommendations for Future Studies. Current Forestry Reports 6(3):185–200. https://doi.org/10.1007/s40725-020-00119-2

Seidl R, Spies TA, Peterson DL, Stephens SL, Hicke JA (2016) Searching for resilience: Addressing the impacts of changing disturbance regimes on forest ecosystem services. The Journal of Applied Ecology 53(1):120–129. https://doi.org/10.1111/1365-2664.12511

Senf, C., Pflugmacher, D., Zhiqiang, Y., Sebald, J., Knorn, J., Neumann, M., Hostert, P., & Seidl, R. (2018). Canopy mortality has doubled in Europe's temperate forests over the last three decades. Nature Communications, 9(1), Article 1. https://doi.org/10.1038/s41467-018-07539-6

Senf C, Buras A, Zang CS, Rammig A, Seidl R (2020) Excess forest mortality is consistently linked to drought across Europe. Nat Commun 11(1):6200. https://doi.org/10.1038/s41467-020-19924-1

Siipilehto, J., Mäkinen, H., Andreassen, K., & Peltoniemi, M. (2021). Models for integrating and identifying the effect of senescence on individual tree survival probability for Norway spruce. Silva Fenn. 55(2), 10496. https://doi.org/10.14214/sf.10496

Sohn JA, Saha S, Bauhus J (2016) Potential of forest thinning to mitigate drought stress: A meta-analysis. For Ecol Manage 380:261–273. https://doi.org/10.1016/j.foreco.2016.07.046

Spiecker H, Kahle H-P (2023) Climate-driven tree growth and mortality in the Black Forest, Germany—Long-term observations. Glob Change Biol 29(20):5908–5923. https://doi.org/10.1111/gcb.16897

Steckel M, Moser WK, del Río M, Pretzsch H (2020) Implications of Reduced Stand Density on Tree Growth and Drought Susceptibility: A Study of Three Species under Varying Climate. Forests 11(6):627. https://doi.org/10.3390/f11060627

Stovall AEL, Shugart H, Yang X (2019) Tree height explains mortality risk during an intense drought. Nat Commun 10(1):4385. https://doi.org/10.1038/s41467-019-12380-6

Swanston, C. W., Janowiak, M. K., Brandt, L. A., Butler, P. R., Handler, S. D., Shannon, P. D., Derby Lewis, A., Hall, K., Fahey, R. T., Scott, L., Kerber, A., Miesbauer, J. W., & Darling, L. (2016). Forest Adaptation Resources: Climate change tools and approaches for land managers. 2nd ed (Issue NRS-GTR-87–2). U.S. Department of Agriculture, Forest Service, Northern Research Station. https://doi.org/10.2737/NRS-GTR-87-2

Taccoen A, Piedallu C, Seynave I, Gégout-Petit A, Nageleisen L-M, Bréda N, Gégout J-C (2021) Climate change impact on tree mortality differs with tree social status. For Ecol Manage 489:119048. https://doi.org/10.1016/j.foreco.2021.119048

Trouvé R, Bontemps J-D, Collet C, Seynave I, Lebourgeois F (2014) Growth partitioning in forest stands is affected by stand density and summer drought in sessile oak and Douglas-fir. For Ecol Manage 334:358368. https://doi.org/10.1016/j.foreco.2014.09.020

Trugman AT, Detto M, Bartlett MK, Medvigy D, Anderegg WRL, Schwalm C, Schaffer B, Pacala SW (2018) Tree carbon allocation explains forest drought-kill and recovery patterns. Ecol Lett 21(10):15521560. https://doi.org/10.1111/ele.13136

Trugman AT, Anderegg LDL, Anderegg WRL, Das AJ, Stephenson NL (2021) Why is Tree Drought Mortality so Hard to Predict? Trends Ecol Evol 36(6):520–532. https://doi.org/10.1016/j.tree.2021.02.001

Vetter D, Storch I, Bissonette JA (2016) Advancing landscape ecology as a science: The need for consistent reporting guidelines. Landscape Ecol 31(3):469–479. https://doi.org/10.1007/s10980-015-0296-z

Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. J Clim 23(7):1696–1718. https://doi.org/10.1175/2009JCLI2909.1

Viechtbauer W (2005) Bias and Efficiency of Meta-Analytic Variance Estimators in the Random-Effects Model. Journal of Educational and Behavioral Statistics 30(3):261–293. https://doi.org/10.3102/10769986030003261

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. Journal of Statistical Software, 36(3), 1–48. https://doi.org/10.18637/jss.v036.i03

Zang CS, Buras A, Esquivel-Muelbert A, Jump AS, Rigling A, Rammig A (2020) Standardized drought indices in ecological research: Why one size does not fit all. Glob Change Biol 26(2):322–324. https://doi.org/10.1111/gcb.14809

Zhang J, Finley KA, Johnson NG, Ritchie MW (2019) Lowering Stand Density Enhances Resiliency of Ponderosa Pine Forests to Disturbances and Climate Change. Forest Science 65(4):496–507. https://doi.org/10.1093/forsci/fxz006

Publisher's Note