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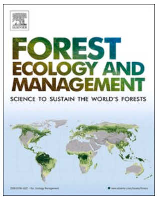

A global synthesis on the effects of thinning on hydrological processes: Implications for forest management

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ABSTRACT

Forest thinning can significantly affect hydrological processes. However, these effects largely vary with forest types, climate, thinning intensity, and hydrological variables of interest. Understanding these effects and their variations can significantly support thinning treatments' design and selection to ensure desired hydrological benefits. In this global-level review paper, we report the first comprehensive meta-analysis on the effects of thinning on major hydrological processes with an emphasis on rainfall partitioning, soil moisture and evapotranspiration processes. The synthesized and reviewed studies encompass different biophysical conditions (climate and forest ecosystems), silvicultural systems, and time scales (from weeks to decades) across continents. The results showed a significant increase in net precipitation, soil moisture and tree-level water use after thinning (the effect sizes are 1.19, 1.14 and 1.56 relative to the value of the control, respectively), while decreases in stemflow and transpiration (the effect sizes of 0.42 and 0.6 relative to the value of the control, respectively). Thinning intensity of about 50% of the stand density is determined as the threshold at or over which hydrological processes are significantly affected. The duration of thinning effect can be set between 2.6 and 4.3 (throughfall) and 3.1–8.6 years (soil moisture and transpiration), asking for repeated thinning in order to effectively sustain these effects. These global averages can serve as benchmarks for assessment and comparisons, but the effects of thinning depend on local biophysical conditions and thinning treatments. The literature review on the rest of the studied hydrological variables suggests that thinning generally enhance runoff to increase water yield and groundwater recharge. Thinning can also have a positive or limited role in water use efficiency (WUE), but it mitigates the effects of drought through increasing WUE. Moderate adverse effects on water quality can be prevented by adequate forest managements to prevent soil degradation. Nevertheless, more researches at relatively less studied regions are needed to support a more robust analysis of these reviewed hydrological variables. The management implications of the synthesized and reviewed results are suggested and discussed within the context of climate change.

1. Introduction

Thinning is a common silvicultural intervention used to reduce stand density and competition so that the remaining trees can grow faster and reach larger diameters. It can be implemented either selectively or systematically and designed with different intensities and goals. In the field of forest hydrology, the research findings on thinning in forested catchments started to appear and intensify through the second half of the 20th century. Before the 1980s, when growth and yield were major forest management objectives, thinning was mainly carried out for timber production. Thereafter, the objectives also looked at understanding the hydrologic response of the thinned stands to develop

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relevant management approaches towards enhanced streamflow and water yield. However, due to the growing concern over long-term forest sustainability, particularly since the 1990s, the objectives of thinning have been expanded to include biodiversity provision (Li et al., 2020), carbon sequestration (Zhang et al., 2018), hydrological functions (Lagergren et al., 2008; Gebhardt et al., 2014; Wang et al., 2019a, 2019b), and fire risk reduction (Taylor et al., 2021). More recently, thinning has been used as a tool for mitigating climate change impacts, as it allows the remaining trees to better cope with droughts (Fernandes et al., 2016; Sohn et al., 2016; Vernon et al., 2018; del Campo et al., 2019b), regulate carbon sequestration (Wang et al., 2020) and reduce climate change-induced disturbance risks (Morán-Ordóñez et al., 2020; Taboada et al., 2021).

Tree removal through thinning reduces the leaf area index (LAI) and canopy interception loss and increases solar energy and precipitation reaching the forest floor. Therefore, it affects most hydrological processes, including rainfall partitioning, soil water redistribution, transpiration, evapotranspiration, and water yield (Cardil et al., 2018). The hydrological consequences of thinning depend on site conditions (forest type and climate), the treatment itself (intensity and type of thinning), the type and duration of observation (spatial scale from individual trees to forest stands and watersheds; time after thinning assessing either short or long-term effects) and target hydrological variables. Typically, increased net precipitation comprised of throughfall and stemflow after thinning is followed by an increase in runoff (Cheng et al., 2020) and enhanced water retention capacity of the catchment, that can help mitigating drought periods (Momiyama et al., 2021), and may assist the resiliency of the ecosystems to the soil water deficit and associated secondary damages (Sun et al., 2015). Thinning has also been used specifically to augment downstream water supply (Kuraji et al., 2019), although increased understory biomass could lead to increased shrub transpiration, compensating the reduced transpiration by trees (Prévosto et al., 2020; Goeking and Tarboton, 2020).

The results of the experimental research on forest management and hydrology have been subject to some global reviews from time to time (Hibbert, 1967; Bosch and Hewlett, 1982; Sahin and Hall, 1996; Brown et al., 2005; Filoso et al., 2017; Goeking and Tarboton, 2020), coming up with similar conclusions that tree harvesting increases streamflow at various levels and durations depending on both the experimental and ecological conditions. A review of 94 catchment experiments to determine the effects of vegetation change on water yield (Bosch and Hewlett, 1982) concluded that, in almost all cases, water yield increased with decreasing forest cover or, conversely, water yield reduced with increasing forest cover. For instance, in small catchments of old-growth eucalypts in central New South Wales, Australia, water yields increased after logging by 150–250 mm per year (Cornish, 1993). The magnitude of this initial increase was directly related to the percentage of the catchment logged (29–70%). No increased water yield was observed where substantial vegetation removal occurred in <20% of the catchment area. Because of the influences of multiple contributing factors over various scales, large variations in hydrological responses to thinning can be expected and the hypothesis of water yield increase following forest cover reduction is no longer universal (Goeking and Tarboton, 2020). Many studies showed that evapotranspiration (ET) often decreased in thinned stands compared to un-thinned ones (Roche et al., 2018; Sun et al., 2017a, 2017b). However, Liu et al., (2018) showed no significant difference in ET between thinned and control. Simonin et al., (2007) and del Campo et al. (2019b) observed even higher stand transpiration in the thinned stand during a severe drought and attributed this to enhanced transpiration of individual trees in the thinned stand during drought as it might have overcompensated the loss of LAI. In addition, Lagergren et al. (2008), and Brooks and Mitchell (2011) measured higher evaporation in thinned stands due to increased wind speed and solar radiation reaching the forest floor. Thinning may also have contrasting effects on the provision of other ecosystem services (Moghli et al., 2022), as for example, it may increase the understory plant diversity by improving light availability, but on the other hand, it may cause a decrease in soil organic matter by reducing litterfall inputs to soil (Blanco et al., 2008).

Temporal and spatial scales are important to understand the effects of forest management on ecohydrological processes. Thinning is generally conducted at the forest stand or plot level, but its ecological impacts extend to landscapes and watersheds (Srivastava et al., 2018). As a general approach, the forest management strategies should address resilience as a long-term objective as well as immediate risks of disturbances (Vilà-Cabrera et al., 2018), implying that understanding the effects of thinning on ecohydrological processes in periods longer than usually reported is necessary. The contrasting results of thinning over space and time highlight that forest management decisions on thinning involve more comprehensive assessment and tradeoff analysis among various ecological services.

The significantly varied and inconsistent results from published studies suggest a need for a quantitative synthesis to generate general conclusions supporting forest management decisions on thinning for various ecosystem services. Some reviews or meta-data analyses have been conducted to synthesize our growing understanding of thinning effects. These reviews often focused on a specific topic such as growth and productivity (Del Río et al., 2017), stand stability and wood quality (Cameron, 2002), understory biodiversity (Li et al., 2020), forest carbon (Zhang et al., 2018), drought stress (Sohn et al., 2016) or fire behavior (Fulé et al., 2012). Reviews of effects on multiple hydrological variables are scarce, and although a recent review covers various topics, it paid attention to only a single forest type (forests dominated by *Pinus sylvestris* L.; Del Río et al., 2017). As far as we know, no reviews (either qualitative or quantitative) have been done on the whole range of hydrological effects of thinning. In addition, although the hydrologic benefits by forest management are well known, as thinning experiments around the globe are not evenly scattered, the level and duration of thinning effects for different climatic regions are still unclear. The main disputable points concentrate around three major issues: level of impacts (i.e., increased annual water yield), duration (i.e. months, years), and tradeoffs among different hydrological effects and other ecosystem services.

This study aimed to review and synthesize the hydrological responses to thinning and further discuss management implications to fill such a critical knowledge gap. To pursue this objective, we conducted both a qualitative (narrative) review and a quantitative meta data-based synthesis to cope with the differences in the number of suitable studies related to different hydrological cycle components. The specific objectives of this review are to: (1) identify the general responses of the hydrological cycle after thinning, including rainfall partitioning, soil moisture, evapotranspiration, tree-water use, runoff, groundwater, water quality, and water use efficiency; (2) explore the differential responses of key hydrological processes to thinning regarding ecological (climate and forest type) and thinning treatment (intensity and time elapsed since thinning) moderators; (3) discuss and recommend forest management strategies based on the synthesized results. The goal is to draw solid conclusions about thinning on the hydrological cycle to be used in strengthening forest management towards mitigating the impacts of climate change.

2. Materials and methods

For this review, we hierarchized the hydrological processes according to the relation and potential impact of thinning: key ecohydrological processes and other hydrological processes. We included both canopy processes (rainfall partitioning and evapotranspiration) and soil moisture as the key processes and streamflow, groundwater, water use efficiency and water quality as the other processes. The key processes have received way more attention in the literature than the other processes, where the literature published prevent from a solid quantitative meta-analysis.

In the key processes, we used the meta-analysis to summarize the results of previous independent studies and analyze general trends. Meta-analyses are useful for exploring complex interactions among factors, large spatial scale patterns across studies, and evaluating factors that may cause heterogeneity in outcomes among studies (moderators). Meta-analyses are gaining attention in forestry and in addressing the effects of forest management (Koricheva et al., 2014). To proceed with the analysis (Koricheva et al., 2013), we (1) performed a systematic review, identifying relevant literature, screening studies, determining eligibility, and evaluating quality and characteristics of studies; (2) extracted and consolidated study-level data including experimental covariates and other study-level characteristics; (3) calculated study-level effect sizes; (4) did the meta-analysis, selecting the model and estimating the true effect size and the heterogeneity in effect sizes; (5) explored the causes of heterogeneity (Mikolajewicz and Komarova, 2019); (6) and evaluated meta-analysis performance by testing for publication bias.

2.1. Systematic review: relevant literature, screening, eligibility and quality of studies

In the systematic review, a search strategy was pre-defined by an explicit statement of the review's objective: studies dealing with the effects of thinning on hydrological processes and comparing them with controls. Related papers were obtained in the summer of 2021 with standard search engines (Web of Science, WOS), including searches in the grey literature in languages other than English (Chinese, Japanese, Korean and Spanish); no restrictions to time span were imposed. The search performed in WOS was TS = (thinning AND Forest AND (hydro* or water) AND (interception or throughfall or evapo* or transp* or *flow*)). The resulting abstracts were screened to remove duplicate studies and irrelevant literature. Next, we examined full texts to ensure they fulfilled the eligibility criteria. In this phase, we excluded papers where thinning was mentioned, but not carried out or where the control treatment was absent. The eligibility criteria included only studies where the thinning treatments and control were comparable (same ecological conditions) and the means, replicates, and standard deviations or standard errors of both treatments and controls were clearly reported or could be extracted out from graphics (Image J software was used for this purpose). Unfortunately, requesting data directly to authors yielded very few positive responses. Throughfall and net precipitation were considered as closely related processes and hence jointly analyzed to increase the sample size. The screening and selection procedure is shown in the PRISMA flow diagram in Figure SM1.

2.2. Extraction and consolidation of study-level data and experimental covariates

Accurate data extraction from selected papers was done, including basic information on the treatment effect size (mean, sample size, and standard deviation for both thinning and control treatments) and moderators. Study-level effect size provides information on the direction and magnitude of the effect of thinning on a standard scale and in an unbiased manner, whilst the sampling variance of the effect size expresses the precision with which the effect is estimated. A common goal in meta-analyses is the analysis of effect sizes and causes of variation that might be due to covariates (or moderators). Moderators to analyze the effects of thinning were selected and extracted out of the selected studies according to their ecological meaningfulness (e.g., climate type, tree species), the treatment characteristics (e.g. time since thinning, thinning intensity), and the methodological features (e.g. the duration of the study, spatial scale). As many studies reported a variety of results according to different thinning intensities or different time spells (e.g., early and mid-term effects of thinning), we opted for retrieving several records accordingly, instead of just a single average record per study that would have overlooked the impact of key moderators. The final list of selected moderators is presented in Table 1. The thinning intensity was considered as an interval variable, according to the removed percentage of either stand basal area (BA, m^2/ha) or stand density (SD, trees/ha). The exact geographical location was extracted to access regional climate and other mapped data (WorldClim.org). If the original paper used other variables or definitions, we converted it to our specific moderators.

A total of 251 observations from 57 peer-reviewed publications were compiled for the different key ecohydrological processes of canopy and soil moisture. The compiled dataset covers a broad range in different biophysical variables, stand characteristics (BA from 5.1 to 107.6 m^2/ha or SD from 200 to more than 40,000 trees/ha) and latitude (from 43°S to 60°N) (Table 1). Study sites included in this meta-analysis are shown in Fig. 1.

2.3. Meta-analysis: the true effect size, heterogeneity and performance

The metafor package in R software (Viechtbauer, 2010) was used to calculate the effect size using random/mixed-effects models. The effect size metric selected was the response ratio or ratio of means (RoM) i.e., the ratio *Mean of Control/Mean of Thinned*, which is frequently used in ecological meta-analysis (Koricheva et al., 2013) whenever the effects being compared have both the same sign (positive or negative) and are different from zero. Typically, the RoM fraction is converted to the ln (RoM) (Crystal-Ornelas, 2020), with a positive number meaning larger value for the numerator (control) and a negative number meaning larger value for the denominator (thinning). The ln (RoM) can quickly be back transformed to the RoM to provide percentage of increase or decrease in the effect of thinning. If the 95% confidence intervals (CIs) of treatment effects do not cover zero, the responses of selected variables to forest thinning are considered statistically significant.

The models first estimated the amount of residual heterogeneity (τ^2 statistic) among the true effects of ln (RoM) with the restricted maximum-likelihood estimator (REML). The null hypothesis Ho: $\tau^2 = 0$ was tested with Cochran's Q-test. The I^2 and H^2 statistics (Higgins and Thompson, 2002) were used to further interpret the estimated amount of heterogeneity. I^2 estimates how much percentage of the total variability in the effect size estimates (which is composed of heterogeneity and sampling variability) can be attributed to heterogeneity among the true effects. H^2 represents the ratio of the total amount of variability in the

Table 1
Moderators selected across studies to study heterogeneity in effect size and descriptive statistics for the quantitative interval-defined variables.

Moderator	Min-Max	Mean	Median	Stand. Dev.
Thinning Intensity (% of BA or SD removed)	14–97%	55/61	52/63	25/24
Years elapsed since thinning	0.5–32.5	3.6	1.5	5.7
Mean annual precipitation (mm)	285–2084	825	700	426
Mean annual temperature (°C)	1.9–27.5	11.3	12.1	4.5
Aridity Index (AI, WorldClim)	0.14–1.72	0.67	0.61	0.42
Potential ET (PET, JRA55)	512–1814	1017	1131	271
LAI of the control (m2/m2)	0.5–8.6	3.2	2.9	1.8
Stand age at the time of the study	3.2–226	40.2	43	29.7
Period of monitoring	Year, growing season, grow. season-dry, non-growing season			
Climate type (Köppen–Geiger)	Tropical Mosoon **Am**, Cold semi-arid (steppe) **BSk**, Hot-summer Mediterranean **Csa**, Warm-summer Mediterranean **Csb**, Temperate oceanic **Cfb**, Temperate Warm **Cfa**, Monsoon-influenced hot-summer humid continental **Dwa**, Monsoon-influenced warm-summer humid continental **Dwb**, Warm-summer humid continental (Hemiboreal) **Dfb**, Subartic **Dfc**.			
Forest type	Hardwoods, coppice, bamboo and softwoods			
Main Species	*Quercus* sp., *Pinus* sp., other hardwoods, other conifers			
Spatial Scale for reported results	Plot, Watershed			

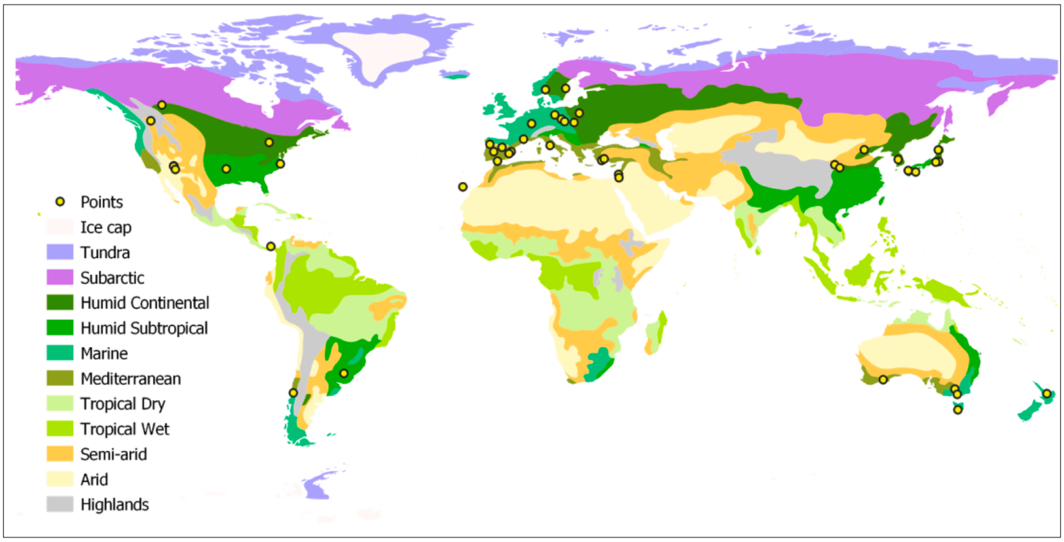


Fig. 1. The distribution of forest thinning experiments (yellow points) selected in this meta-analysis according to basic climatic zones (https://ggis.un-igrac.org/layers/igrac:igrac:Climate_Zones_WGS84.shp). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

observed outcomes to the amount of sampling variability (therefore, if $\tau^2 = 0$ then $H^2 = 1$). Then, the estimators for the true effects were estimated via weighted least squares and the Wald-type test and confidence intervals were obtained (Viechtbauer, 2010).

Part of the heterogeneity in the true effects may be caused by the influence of the moderators, which was examined by fitting mixed-effects models including either categorical or interval-defined moderators (Table 1). When the model showed a significant omnibus test (Q_M), the coefficients of the moderators were estimated in the same way as mentioned above. The publication bias was evaluated by funnel plots, where the studies must be distributed symmetrically in a 'funnel' shape around a mean effect size.

3. Effects of thinning on hydrological processes with meta-data analysis

Thinning had a significant effect size on all the ecohydrological processes meta-analyzed except for total evapotranspiration. The effect sizes representing outcome in magnitude and direction are shown in Table 2 and Fig. 2. Stemflow, total evapotranspiration and stand transpiration were significantly lower in the thinning treatments (0.42, 0.96 and 0.6 the value of the control, respectively), whereas throughfall (and net precipitation), soil moisture, and tree-level water use or sap flow were significantly increased with thinning (1.19, 1.14 and 1.56 the value of the control, respectively). As expected, these values were significantly affected by the three classes of moderators considered: ecological (climate, type of forest, species), treatment intensity, and research timeframe (the period reported, the time elapsed since thinning). These results are presented and detailed in the following sections.

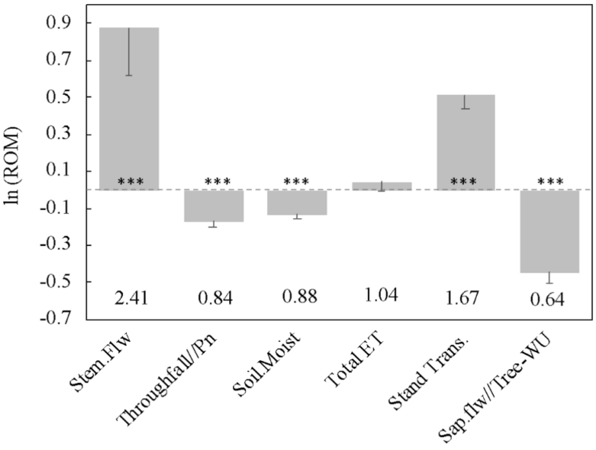


Fig. 2. The estimated ln (RoM) of the mean effect size of forest thinning on studied hydrological processes (Stemflow, Throughfall and Net Precipitation, Soil Moisture, Total ET, Stand transpiration and Tree-level water use). The metric ln (RoM) represents the *natural logarithm of the ratio Control_mean/Thinned_mean*, with a positive number meaning larger value for the numerator (control) and a negative number meaning larger value for the denominator (thinning). Error bars represent standard error of the mean. Figures on the lower part of the plot are the value of exponentiating ln (RoM) (i.e., the ratio Control/Thinned). *** Significant at p-value < 0.001.

Table 2
Summary of random effects models fit to the hydrological processes of Stemflow, Throughfall (and Net Precipitation), Soil Moisture, Total ET, Stand Transpiration and Tree-level water use. ln (RoM) is the estimated average effect size, i.e. ln (Control/Thinned); and CI-lb and CI-ub represent the lower and upper boundaries of the confidence intervals, respectively. *** p < 0.001. Full models detailed in Table SM1.

Hydrological process	Estimate ln (RoM)	Standard error	z-value	CI-lb	CI-ub
Stemflow	0.88	0.26	3.39***	0.371	1.39
Throughfall and Net Precip.	−0.171	0.028	−6.05***	−0.226	−0.116
Soil Moisture	−0.132	0.0251	−5.274***	−0.181	−0.083
Total ET	0.043	0.0527	0.822	−0.06	0.1466
Stand Transpiration	0.514	0.0734	7.010***	0.371	0.658
Tree-WU	−0.446	0.058	−7.686***	−0.560	−0.332

3.1. Canopy interception processes

Rainfall partitioning (RP) is the first, direct, and typical hydrological response to precipitation in forest ecosystems, and thus it is the principal hydrological process affected by thinning. Precipitation, generally called as gross rainfall and snowfall (*Pg*), is partitioned into three components at the forest canopy: (1) throughfall (*Tf*) consisting of free throughfall, drip, and splash, (2) stemflow (*Sf*), and (3) interception loss (*Il*). The sum of *Tf* and *Sf* is called net precipitation (*Pn*). RP processes are double-edged swords having both negative and positive effects on hydrological functions. For example, *Il* is the loss of water resources but also plays a critical role of decreasing the risks of floods and soil erosion as it reduces the net precipitation during heavy storm events. RP processes, especially *Tf* and *Sf*, are also important for geochemical science because the materials contained in rainwater are largely changed and consequently affect nutrient flux during RP processes. Therefore, RP processes have been widely investigated in both hydrology and geochemistry for a long time.

There are a considerable number of review papers on RP processes: *Il* (Horton, 1919; Clarke, 1986; Muzylo et al., 2009), *Tf* (Sievering, 1987; De Schrijver et al., 2007a, 2007b; Levia et al., 2017, Serio et al., 2019), *Sf* (Levia and Frost, 2003; Ikawa, 2007, Levia and Germer, 2015, Van Stan and Gordon, 2018), and RP (Llorens and Domingo, 2007; Magliano et al., 2019; Yue et al., 2021). Among them, two papers conducted a meta-analysis of RP processes: Magliano et al. (2019) for dryland and Yue et al. (2021) for the globe. Yue et al. (2021) analyzed RP processes of trees and shrubs using 2430 observations from 236 independent publications and reported that the RP ratios (ratios of RP to *Pg*) widely ranged across the globe; *Tf* ratios: 7.8–98.1% (median 73%), *Sf* ratios: 0–43.8% (median 3.2%), and *Il* ratios: 0.4–90.9% (median 21.8%). Although there are a number of review papers on RP processes as mentioned above, there are no review papers on the effects of thinning on RP processes.

The papers on the effects of thinning on RP processes are classified into three categories: (1) direct measurement of the spatial comparison having control plot (e.g. Aussenac and Granier, 1988; Ma et al., 2020), (2) direct measurement of the temporal comparison having control period (eg. Crockford and Richardson, 1990a,b; Nanko et al., 2016), and (3) analysis using the RP data in the previous papers on the assumption that the stand densities (SD, trees/ha) of studied forests were affected by thinning (eg. Komatsu et al., 2015; Sun et al., 2017b; Jeong et al., 2020).

For the review of papers categories (1) and (2) on the impact of thinning on RP processes conducting the direct measurements, we collected 26 papers explicitly showing the values of RP components or RP ratios, which included 34 observations (Table 3 and Supplementary Material SM2). Seventeen papers (with 40 records in total) out of them were suitable for meta-analysis of *Tf* and *Pn* (Figure SM2) and only nine (12 records) for meta-analysis of *Sf* (Figure SM3; in this case, the influence of moderators could not be performed). If possible, the unreported RP components were calculated from the other reported RP components and added as the obtained values; for instance, unreported *Il* was calculated from the other reported *Tf*, *Sf*, and *Pg*. The observations were conducted during 1988–2020 mostly in Asia (16) and Europe (13). Twenty-seven observations were on softwoods (26: evergreen conifer, 1: deciduous conifer), and seven on hardwoods (4: evergreen broadleaf tree, 3: deciduous broadleaf tree). The age of the trees and stand structures were widely ranged; age: 7–66 years (median 22 years), diameter at breast height (DBH): 2.7–33.2 cm (median 18.0 cm), basal area (BA): 4.0–107.6 m^2/ha (median 28.0 m^2/ha), SD: 178–11300 trees/ha (median 1200 trees/ha). Thinning intensities were also widely ranged: 8.0–74.1% of BA removed (median 42.5%) and 8.2–93.8% of SD removed (median 49.0%). Among 34 observations, 19 were spatial comparisons, and 15 were temporal comparisons, including 39 control and 48 treatment plots, and the time after the thinning ranged 0–9 years (median 1 years). Although the observations differed considerably as summarized above, the tendencies of the reported impacts of thinning on RP processes had a significant ln (RoM) of 0.88 and −0.17 for *Sf* and *Tf,* respectively (Table 2; Fig. 2), and heterogeneity was also significant (Q test, $p < 0.0001$, Table SM1). The moderators thinning intensity, years elapsed, climate, forest type, period, and species showed significant omnibus test (Q_M) on the effect size of thinning on *Tf* and *Pn* (Table SM1 and Fig. 3-top). Thinning significantly enhances *Tf* ratio because it releases the canopy closure and makes free throughfall, drip, and splash easily fall on the forest floor. On the other hand, *Sf* ratio is significantly decreased with thinning because it reduces the canopies and stems to collect rainwater at least for a certain number of years after thinning.

Table 3
Summary of RP ratios of 28 observation of thinning. C and T stand for control and thinned respectively. Incr. and Decr. represent the number of studies with increment or decrement respectively in the RP process with thinning.

RP	Min		Median		Max		Incr.	Decr.
	C	T	C	T	C	T		
	(%)	(%)	(%)	(%)	(%)	(%)	(Tx)	(Tx)
Tf	51.8	61.2	67.5	80.6	200.1	222.3	33	3
Sf	1.6	0.1	8.5	4.8	14.4	9.5	1	14
Il	10.7	4.5	26.6	19.0	42.5	38.4	1	29
Pn	57.5	61.6	76.0	81.0	89.4	95.5	29	1

Among 36 studies (Table 3 and Supplementary Material SM2), *Tf* ratios increased in all but in 3 studies (Fig. 3-top and Figure SM2). Slodicak et al. (2011) reported long-term observations of *Tf* after the heavy-low thinning at the age of 7 and the light-high thinning at the age of 16. Compared to the control plot, the *Tf* ratio of thinned plots slightly increased after the first heavy-low thinning but showed a slight decrease after the second light-high thinning. The authors implied that the application of light-high thinning increased variability of the canopy with less release of crowns. In Gavazzi et al. (2016) a rapid increase of the understory one year after thinning in a climate type Cfa explained the reduction of *Tf* ratio by thinning (Figure SM2). In fog-dominated forests, the *Tf* ratio increased in lightly thinned plots but decreased in heavily thinned ones nine years after thinning (Aboal et al., 2000; climate type Csb), because the lightly thinned plot grew close to the control plot (with similar BA and LAI), highlighting the specific hydrological behavior of fog dominated ecosystems, more affected by the fog entrapment functions than the RP function of the stands.

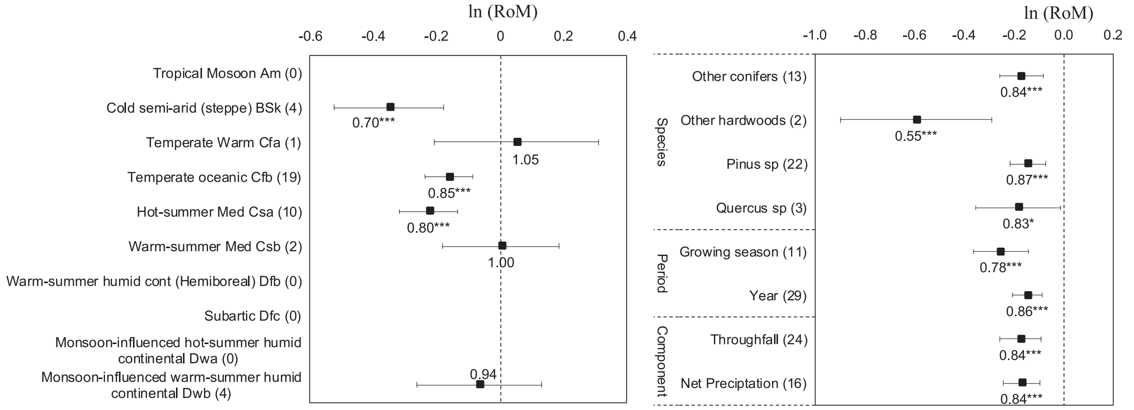
Among 15 studies, *Sf* ratios decreased with thinning in all of them but one (Kim et al., 2004), (Table 3, Figure SM3) where the observations were performed eight years after thinning (in contrast to 1–3 years after thinning as reported in the other studies). The authors suggested that the slight increase of *Sf* ratio in *Abies holophylla* after thinning was likely because of larger diameter classes as compared to the control plot. Since the number of trees was almost half, but individual tree BA was nearly two times larger than the control plot, *Sf* ratio could be almost the same between the thinned and control plots if the funneling ratios (*Fr*) of two plots were similar. It should be noted that trees with larger DBH tend to have smaller *Fr* in general (Jeong et al., 2020), and *Fr* in this treatment could be increased due to the expansion of the canopy during eight years after thinning. This could be the reason why the *Sf* ratio slightly increased after thinning in this treatment.

Among 30 studies, *Il* ratios decreased with thinning in 29 (with the above-mentioned exception of Gavazzi et al, 2016) (Table 3), pointing out that, in terms of canopy water balance, the larger increase of *Tf* ratio and smaller decrease of *Sf* ratio by thinning caused *Il* ratio being reduced.

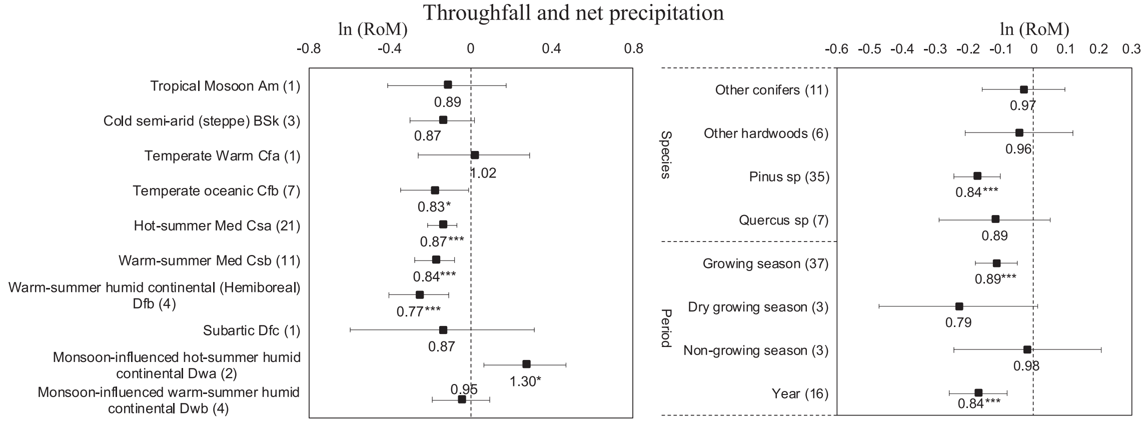
The category (3) RP studies analyzing the data in the previous papers were generally applied to model the thinning effect on RP, especially for plantations. Since the stand characteristics of plantations change over time by artificial-thinning or self-thinning with a certain regularity, the assumption that the studied forests' SD was affected by thinning could hold true. Komatsu et al. (2015) collected 45 reported data of *Il* ratios and the related stand structures of two major trees of Japanese conifer plantations (*Cryptomeria japonica* and *Chamaecyparis obtuse*) across Japan and made the following *Il* ratio estimation model as a function of SD.

$$Il/Pg = 0.308\{1\text{-exp}(-8.8 \times 10\hat{}(-4) \times SD)\}.$$

Jeong et al. (2020) collected 18 reported data of *Sf* ratios and the related stand structures of *C. japonica* and *C. obtuse* across Japan and found that SD is the most influential stand characteristic for *Sf* and the single linear regression equation of *Sf* ratio as a function of SD had a



Throughfall and net precipitation



Soil moisture

Fig. 3. Mean effect sizes (ln (RoM) is the *natural logarithm of the ratio Control_mean/Thinned_mean*, with a positive number meaning larger value for the control and a negative number meaning larger value for the thinned) of forest thinning on throughfall and net precipitation (two upper panels) and on soil moisture (two bottom panels) by categorical moderators (Köppen–Geiger climate type, main species and period of the year assessed). Error bars represent 95% confidence intervals (CIs). The fraction of change (Control/Thinned) for each variable is shown next to the point. The number in parentheses represents the sample size for each variable. Significance codes: <0.001 '***', <0.01 '**', <0.05 '*'.

sufficient degree of accuracy. Additionally, by introducing the obtained stand-level *Fr* model as a function of DBH, a new estimation model of *Sf* ratio as a function of DBH and SD was proposed, which had higher accuracy than the single linear regression equation with SD.

Sf/Pg = 1.373 × 10ˆ(-4)×(DBH) ¯ˆ0.5155 × SD).

Sun et al. (2017b) conducted the joint project of thinning experiments of *C. japonica* and *C. obtuse* at seven experiment sites with various stand structures across Japan and collected the *Tf* ratios and the related stand structures from the project, and proposed the following *Tf* ratio estimation model as a function of SD, canopy coverage (CC, %), and BA.

Tf/Pg=(-0.0129 × SD-0.2818 × CC + 0.1388 × BA + 103.0985)/100.

In the regions where the data of RP and the related stand structure characteristics are sufficiently reported or obtained, such as the above-mentioned examples, the effects of thinning on RP could be estimated using common forest inventory data with a sufficient degree of accuracy.

3.2. Soil moisture

Soil processes constitute a major component of the hydrological cycle in forest ecosystems and affect forest growth, productivity, and other functions. These processes are affected not only by bio-climatic conditions such as precipitation, forest type, and soil properties but also by forest management interventions. Thinning as a management tool affects tree cover and in turn influences soil processes, especially soil moisture (SM). Therefore, many studies investigated the effects of thinning treatments on forest SM (Schmidt-Walter et al., 2020).

There are a considerable number of review papers on forest SM, such as Ruarkj et al. (1983), Robinson et al. (2008), Seneviratne et al. (2010), Wang et al. (2019a). Among them, the recent review of Wang et al. (2019a) recognized SM as a key ecohydrological variable in analyzing the soil–plant–atmosphere interactions and reviewed approaches for investigating SM–plant interactions in order to predict plant/ecosystem responses to SM variations under climate change. The review revealed that the status and distribution of SM affected ecohydrological processes (e.g., runoff, infiltration, and evaporation) and plant function (e.g., transpiration and photosynthetic rate). Plants also affect SM dynamics through its involvement in the hydrological cycle. They concluded that long-term and controlled experiments investigating SM dynamics and a meta-analysis of the studies were crucial to better understand and quantify the SM–plant interactions.

We reviewed 21 studies reporting quantitative results about the effects of thinning on SM and extracted a total of 55 records out of them for the meta-analysis of their size effects. SM was reported in various units (including soil water content SWC %, relative extractable water REW % and mm), time intervals, and different soil depths. The latter could not be addressed as moderator, and we used the depth range of 15–50 cm as the reference whenever several soil horizons were reported (e.g., Xu, et al., 2020). The studies were conducted between 1992 and 2021, mostly in Europe (5) but also in Asia (6) and America (7). The altitudinal range of study areas was between 90 and 1300 m asl (median 1090 m asl). These studies included 8 observations on hardwoods (3 Cfb, 2 Csb, 1 Am, 2 BSk), 49 observations on softwoods (9 Csb, 1 Dfc, 19 Csa, 4 Dfb, 4 Cfb, 2 Dwa, 4 Dwb, and 1 BSk), two observations on coppice (2 Csa) and one on bamboo (Cfa). The age of the trees and stand structures were widely ranged: age: 8–226 years (median 24 years), BA: 5.6–90 m^2/ha (median 29.7 m^2/ha), SD: 947–54,700 trees/ha (median 2160 trees/ha). Thinning intensities were also widely ranged: 1–46% of SD removed (median 24%). Thinning treatments were mostly from below (15 experiments), heterogeneous spatial structure (3 experiments), precommercial thinning (8 experiments), and regular spacing (18 experiments) and all investigated in the plot level.

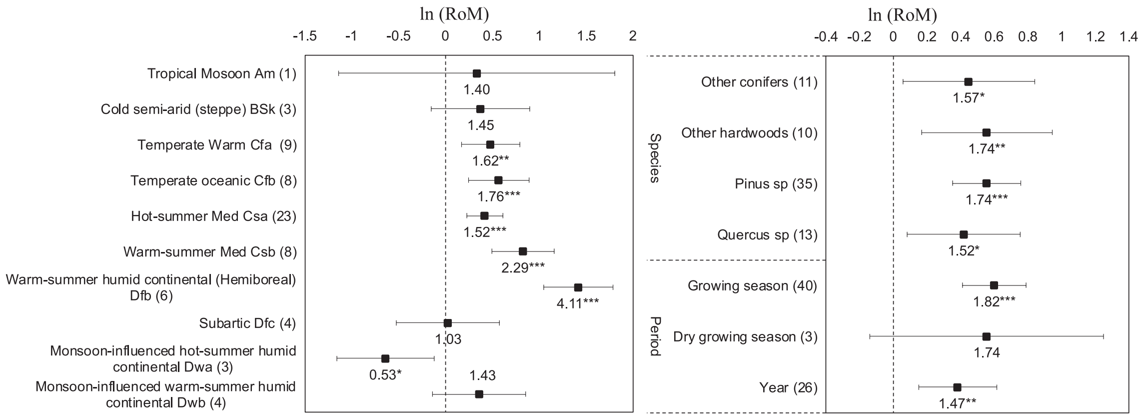
The random and mixed-effects models fit for SM estimated an average ln (RoM) = −0.13 ($p\text{-value} < 0.0001$, $C/T = 0.88$ after exponentiation). The test for heterogeneity (Q) among the true effects of ln (RoM) identified considerable and significant heterogeneity for the effect of thinning on SM ($\tau^2 = 0.028$, $I^2 \geq 90\%$), that was partly due to moderators (Table SM1). Mixed-effects models demonstrated that part of the total amount of heterogeneity can be accounted for by including either categorical or continuous moderators, with significant omnibus test (Q_M) for climate type, species, thinning intensity, time elapsed and period reported (Table SM1 and Fig. 3-bottom). For thinning intensity, either 25% (SD removed) or 18% (BA removed) of the total amount of heterogeneity was due to this moderator (Table SM1). Köppen–Geiger climate type accounted for 23% of the total heterogeneity (Table SM1). Among climate types, the mean effect size was the highest in regions with warm-summer humid continental climates (Dbf) and, among forest species, the effect size was the highest for *Pinus* sp. with 77% and 84% for the ratio C/T, respectively (Fig. 3-bottom). However, only four records in one study (Wang et al., 2019b) carried out in warm-summer humid continental climates (Dbf) located in a southern interior British Columbia obligate for caution on this result (Figure SM4). In this sense, the relevant magnitudes and direction of the effects size are those for Csa and Csb climates (Mediterranean with either hot or warm summer) and *Pinus* sp., with a ratio C/T of about 0.85 ($p\text{-value} < 0.001$). Most of the effect sizes were positive for all climate types except for warm temperate Cfa and monsoon-influenced hot-summer humid continental Dwa, with very low sample size (Fig. 3-bottom). In the other categorical moderators, the effect size on SM was always positive, although only significant in *Pinus* sp. ($p < 0.001$). Given these results, the sample size appears as a critical factor affecting the analysis results, with the effect size trending to be significant with increasing sample size.

The forest plot in Figure SM4 shows the effect size of thinning on SM for both the individual studies and the overall mean, revealing wide sampling variance among studies (Figure SM4). Most of them showed negative ln (RoM), with the largest negative value being −1.01 ($-1.85 < CI < -0.16$) (Jimenez et al., 2008) in a young 8-year-old post-fire overstocked *Pinus pinaster* stand in NW Spain treated with very intensive thinning (leaving a residual SD of 1925 and 3850 saplings/ha respectively) besides a control (40200 saplings/ha). The study by Molina et al. (2021) in a mature *Pinus halepensis* plantation (in E Spain) had the smallest CI among studies (ln (RoM) = −0.35, $-0.39 < CI < -0.32$) and had one of the largest magnitudes (large effect) among studies. Here, different thinning intensities were evaluated after 10 years, with forest cover ranging from 83% in the control to 16% in the highest intensity treatment. A high positive ln (RoM) was shown by Chen et al. (2020) (0.49, $0.40 < CI < 0.57$) who investigated the effects of thinning conducted in 1981 in a catchment dominated by *Pinus tabuliformis* (5000 saplings/ha). Low, medium, and high dense stands with 983, 1688, and 2160 trees/ha, respectively, were evaluated in 2012–2014 and showed that thinned stands had a higher mean DBH and exhibit higher canopy transpiration. Moreover, there is always high variability within different records of a single study, e.g., Xu et al. (2020) showed a range from positive to negative in ln (RoM). This study analyzed the stand water balance after thinning during an extremely wet and dry year in a *Larix principis-upprechtii* Mayr. plantation in the water-limited Loess Plateau of NW China and found that thinning decreased transpiration and interception loss, while increasing understory evapotranspiration and water yield. Overall, the study concluded that thinning improved the stand-level SM due to the increased throughfall in the Larch plantation. In contrast, the experiments by Zheng et al. (2019) studying *Robinia pseudoacacia* L. responses to thinning intensity in a catchment within the central Loess Plateau in China showed a low range of change in effects size of thinning on SM. They stated that *R. pseudoacacia* L. plantations might actively adjust their photosynthetic functions immediately in the first growing season after thinning. It can be summarized from the forest plots that a juvenile pre-commercial thinning on pine saplings had the highest effect on SM (Jimenez et al., 2008; Wang et al., 2019a, 2019b; del Campo et al., 2019a) with mean ln (RoM) = −0.41 and C/T = 0.66.

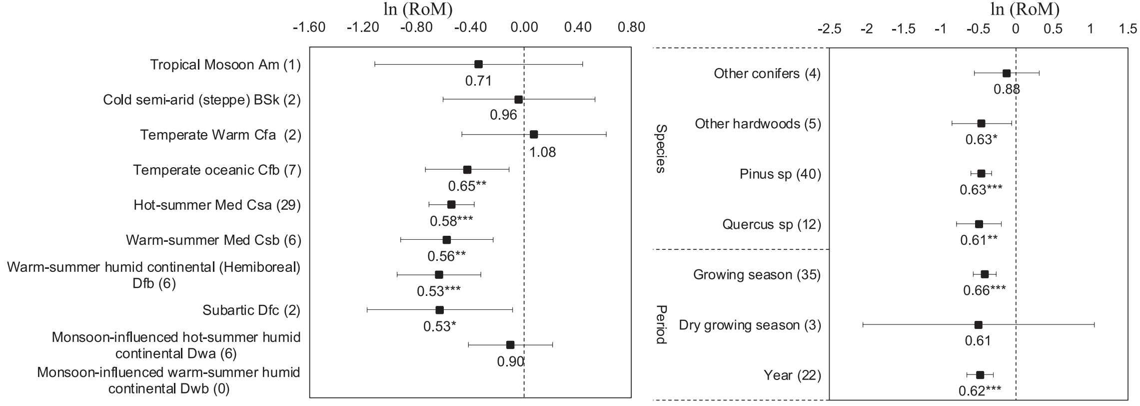
3.3. Evapotranspiration, stand transpiration and tree-level water use processes

This section includes total evapotranspiration (ET), stand transpiration (T) and tree-level water use (or sap flow, SF), which represent the largest share of water fluxes in the hydrological cycle of forest ecosystems and are of prime interest in water-oriented forest management (Jasechko et al., 2013). Forest ET is partitioned into three components: plant transpiration, soil evaporation, and interception loss (water bodies evaporation is beyond the scope of this analysis). In this part, we focused on ET, T, and SF as interception loss is addressed in 3.1. and soil evaporation has received very little attention in the literature reviewed. However, studies reporting ET as the output of modeling included all three components for the whole watershed (Gonzalez-Sanchis et al., 2019; Liu et al., 2018; Moreno et al., 2016). Empirical plot-based determinations including the three components of ET separately are also found (Sun et al., 2017a, 2017b; del Campo et al., 2019b). Only one study reports the understory contribution to ET (Simonin et al., 2007). Therefore, ET represents a heterogeneous set with a lower sample size (12 studies and 20 records) in contrast to studies on the effect of thinning on T and SF (31 studies and 68 records for T and 21 studies with 57 records for SF). The units reported for ET and T were in most cases either mm or percentages of gross rainfall (*Pg*) for different time spells. Daily ET (on year basis) averaged 1.44 ± 0.88 mm/day, whilst T averaged 0.67 ± 0.43 and 0.46 ± 0.27 mm/day for control and thinning respectively. SF was reported in a much wider range of units (besides the variability in the time interval), including mmol, g, mm and l, that in some cases are per unit of area (canopy, leaf, sapwood) or for the whole tree in others. Daily SF (on year basis) averaged 6.9 ± 3.96 and 11.6 ± 5.81 l/tree·day for control and thinning, respectively.

For ET, T and SF, the estimated mean ln (RoM) is 0.04, 0.51, and −0.45, respectively (Table 2; Fig. 2). Their exponentiation resulted in greater ET and T in the control by 4 and 67%, respectively, than in the corresponding thinning treatments. In contrast, SF in the control is 0.64 times the value of the trees remaining after thinning (i.e., 57% higher in the treatment). These differences were statistically significant ($p < 0.0001$) except for ET (the null hypothesis Ho: $\mu = 0$ cannot be rejected; $z = 0.822$, $p = 0.411$). There was considerable and significant heterogeneity (Q test, $p < 0.0001$) among the true effects of ln (RoM) for all the three variables (Table SM1). The influence of moderators on the total amount of heterogeneity was analyzed for T and SF, as thinning had a significant effect on these processes. In T, several models showed a significant omnibus test (Q_M) either for categorical or interval-defined moderators (Table SM1, Fig. 4-top). In particular, the models fited for Köppen–Geiger climate type ($\tau^2 = 0.208$, i.e., 40% of the total amount of heterogeneity was due to this moderator), for thinning intensity (% of BA removed, $\tau^2 = 0.226$, i.e., 35% of heterogeneity) and years since thinning (17% of heterogeneity), showed an important contribution on the effects of thinning on T. In the case of climate, the types with lower sample size present greater confidence intervals that prevent significance. In warm and hot-type climates (higher sample size) T of the control was always significantly higher, standing out the value of RoM for Dbf climate-type (4.11) where a juvenile thinning on lodgepole pine in southern British Columbia (Wang et al., 2019b) notably biased this value. A lower ratio in hot-summer Mediterranean climates (1.52) is likely pointing out to a higher contribution of summer soil water deficit, which imposes low water consumption rates in the controls. This effect could also explain the higher effects observed for thinning on T in pines than in oaks (the moderator of main species), as oaks were mostly



Stand transpiration



Tree water use and sap flow

Fig. 4. Mean effect sizes (ln (RoM) is the *natural logarithm of the ratio Control_mean/Thinned_mean*, with a positive number meaning larger value for the control and a negative number meaning larger value for the thinned) of forest thinning on stand transpiration (two upper panels) and on tree-water use (SF) (two bottom panels) by categorical moderators (Köppen–Geiger climate type, forest ecosystem type and period of the year assessed). Error bars represent 95% confidence intervals (CIs). The fraction of change (Control/Thinned) for each variable is shown next to the point. The number in parentheses represents the sample size for each variable. Significance codes: <0.001 '***', <0.01 '**', <0.05 '*'.

studied under Csa climates (Schiller et al., 2003; Moreno and Cubera, 2008, del Campo et al., 2019b, Gavinet et al., 2019). Regarding the effects of thinning intensity, the positive slope in the regression models (Fig. 5 and Supplementary Material SM3) for this moderator indicates a direct relationship between % of SD removed and ln (RoM); actually, the average C/T for the 30 records with thinning intensity higher than 50% was C/T = 2.3. In the same way, every year elapsed after thinning decreased the ln (RoM) (Fig. 5 and Supplementary Material SM3), reflecting a dampening effect of thinning with time. In fact, the studies reporting T for more than 10 years average C/T = 1.27 (Moreno and Cubera, 2008; del Campo et al., 2014; Chen et al., 2020; Molina et al., 2021).

In the case of SF, part of the heterogeneity was also due to either categorical or interval moderators (Table SM1 and Fig. 4-bottom). In this case, the models including the Köppen–Geiger climate type (τ^2 = 0.148, i.e., 11.3% of the total amount of heterogeneity was due to this moderator) and the thinning intensity (% of SD removed, τ^2 = 0.133, i. e., 20,5% of the heterogeneity) showed important explanation of the total amount of heterogeneity. The Fig. 4-bottom in conjunction with Fig. 3 (RP and SM), demonstrates that more available water and resources promoted by thinning improve the tree-based SF.

Forest plots (Figures SM5 to SM7) provide a detailed picture of the effect size by individual studies. In the case of ET, even though the sample size was small, the individual records pointed out to a very slight increase of ET in the control, with one study (Simonin et al., 2007) outlying with an opposing trend. These authors included the understory-water use, an aspect that received very little attention in the literature and might be of prime importance under semiarid conditions (Goeking and Tarboton, 2020). In fact, filtering in by an aridity index (AI) < 0.5, results in a ln (RoM) = -0.06 and C/T = 0.94, suggesting a slight increase in total ET with thinning in these works (Simonin et al., 2007; Dore et al., 2010, 2012; del Campo et al., 2019b; Gonzalez-Sanchis et al., 2019; Moreno et al., 2016). In the case of T, the forest plot shows higher heterogeneity, and only one outlier with different sign to that of the overall effect size, that of Chen et al., (2020), who studied the effect of three thinning intensities (between 22 and 54% of SD removed) after 30 years without using an un-thinned control. To supply the lack of control in this work, we used the lowest intensity (2160 trees/ha) as the control, but even then, the sparse trees showed higher T as already mentioned in the SM section 3.2. On the other hand, juvenile thinning on *Pinus* sp. (Whitehead and Kelliher, 1991; Jimenez et al., 2008; Munka et al., 2013; Wang et al., 2019b) had the highest effect on T (C/T = 3.7 when filtering in by age < 15 years and *Pinus* sp.). Finally, for SF, it can be noticed from the forest plot the lower value in the studies performed in the driest zones (Schiller et al., 2003; Simonin et al., 2006; del Campo et al., 2014, 2019b; Bayar and Deligöz, 2020; Molina et al., 2021) with AI < 0.5, and ln (RoM) = -0.92 or C/T = 0.40. This is related to the enhancement of tree vigor and resilience to climate change in these drier sites, reinforcing the role of thinning as key adaptive treatment in water-stressed forests (Grant et al., 2013).

3.4. Integrated assessment of canopy and soil moisture processes

In this study, we have proved that, globally, thinning has significant

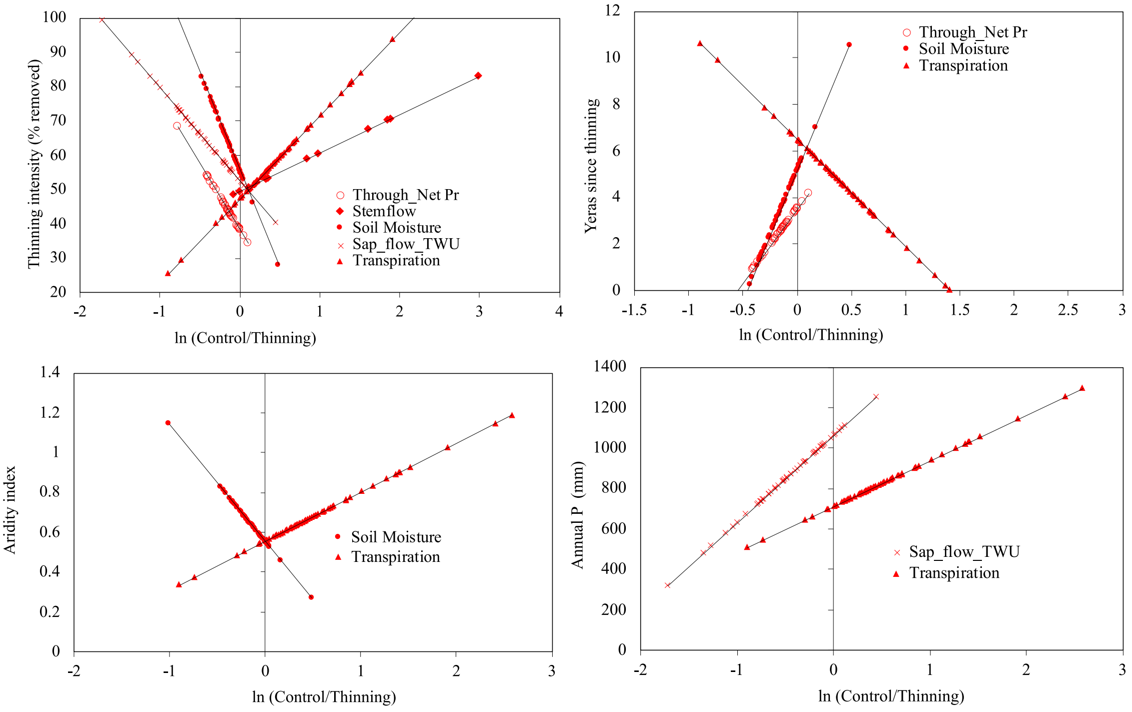


Fig. 5. Regression models fit between the effects size (ln (RoM) is the ln *of the ratio Control/Thinned*, with a positive number meaning larger value for the control and a negative number meaning larger value for the thinned) of the different hydrological processes and the interval-defined moderators significant in the meta-analyses. Hydrological processes: Stemflow (Sf), Throughfall (and Net Precipitation) (Tf_Pn), Soil Moisture (SM), Stand Transpiration (T) and Tree-level water use (SF). %BA Rem: Thinning Intensity (% of basal area removed); %SD Rem: Thinning Intensity (% of stand density removed); Years Thin: Years elapsed since thinning; Pg: Mean annual precipitation (mm); AI: Aridity Index. In all the cases the models were significant, and both the slope and the intercept were significant too. Table 4 and SM3 (full models) provide additional details on the regressions performed.

effects on RP, SM, T and SF that in turn are mediated by the three sorts of moderators chosen (ecological, technical and scope of the study). In general, the climate type (Köppen–Geiger) has been a key moderator onto these effects, accounting for 11–40% (Table SM1) of the total heterogeneity observed, with larger effect sizes observed in either hot or warm summer climates (Csa, Csb, Dfb). The influence of thermality was also present in the period assayed (moderator), showing a more marked effect of thinning in *Tf, Pn* and T, in the growing season than year-round (Figs. 3 and 4), which calls for caution when extrapolating results from isolated periods to longer time windows. The missing piece in this picture is ET, which despite higher *Pn* and lower T under thinning, resulted insignificant in the analysis, posing doubts about the usefulness of thinning as means of water provisioning. As T only reflects the contribution of the remaining trees after thinning to ET, it could be thought that water-use of understory vegetation (shrubs, herbs, grasses, and other perennials) and evaporation from soil could have offset both higher *Pn* and lower T, as reported in some studies (Simonin et al., 2007; del Campo et al., 2019b, Goeking and Tarboton, 2020). On the other hand, the source for ET (excluding *Il*) is SM, which was significantly negative (thinned is wetter) in most studies and especially in young and overstocked pine stands. Then, it can be argued that ET could be also lower after thinning at global scale, and the weak point of our analysis would be the small sample size found for ET studies, which is well known to bias the power of meta-analyses (Rosenthal, 1979). Given that ET partitioning is challenging at the usual plot scale employed in most experimental setups (where both control and thinning are reiterated in small patches of less than a few thousands of square meters), SM is likely a key (proxy) variable to strengthen and focus on future studies from both methodological and reporting sides. The effect size found for SM, showed high sampling variance (Figure SM4), expressing low precision of the effect even within different records of individual studies (e.g., Breda et al., 1995). Funnel plots (Figure SM8) did not show plot asymmetry and thus no publication bias can be expected in the results of meta-analyses.

In the interval-defined moderators, thinning intensity showed the most significant effect on hydrological processes (RP, SM, T and SF) and the linear models obtained for this moderator (Table 4, Fig. 5 and supplementary material SM3) provide an estimated average of about 50% of SD removed in order to promote a significant departure from the control of the effects reported in the different processes. This value is somewhat lower for BA, as expected from the observed sample, and is below the total average of the reviewed works (Table 1). The effects of thinning have also been shown to depend on the time elapsed since cutting (with less variability explained by the models although significant for *Tf, Pn*, SM and T) pointing out to a lasting effect shorter than expected (between 3.5 and 6.5 years depending on the process). The fact is that the median time in our database is only of 1.5 years (Table1) with very few studies reporting effects after 5 years of the treatment, and they average ln (C/T) values of 0.27 and −0.07 for T and SM respectively (about half the size effect in Table 2). Slodicak et al., (2011) showed a significant effect of thinning on *Tf* of 4 years. Finally, interval-defined climatic moderators explained low heterogeneity (R2 < 15% in all cases Table SM1) but according to them (Fig. 5 and supplementary material SM3, aridity index (AI) and precipitation (*Pg*) have affected the size-effect of different processes (SM, T and SF), with drier climates (AI < 0.42) showing moderate or little effects of thinning on either SM or T, and sub-humid and humid climates (*Pg* > 710 mm) enhancing the effect size of thinning on T.

4. Effects of thinning on other hydrological processes

4.1. Streamflow

Streamflow is the difference between precipitation and

Table 4

Intercepts (reported with their standard error and 95% confidence intervals) of the regression models fit between the effect size (ln (C/T)) of the different hydrological processes and the significant moderators (interval-defined) identified in the meta-analyses. The intercept is for the model *moderator* = *incercept* + *b**ln*(C/T),* which gives the value of the moderator for an effect size of zero (i.e., ln (C/T) = ln (1) = 0). Hydrological processes: Stemflow (Sf), Throughfall (and Net Precipitation) (Tf_Pn), Soil Moisture (SM), Stand Transpiration (T) and Tree-level water use (SF). Number in parenthesis is the sample size in each process. %BA Rem: Thinning Intensity (% of basal area removed); %D Rem: Thinning Intensity (% of density removed); Years Thin: Years elapsed since thinning; P: Mean annual precipitation (mm); T: Mean annual temperature (°C); AI: Aridity Index; Age: Stand age at monitoring time. In all the cases the models were significant, and both the slope and the intercept were significant too. (*) not identified in the meta-analysis, but with significant regression. Full models are provided as SM3.

Hydrol. Process	Moderator	Intercept coefficient	Standard error (SE)	Lower 95%	Upper 95%	R^2
Sf (12)	%SD Rem*	49.4	5.7	36.7	62.1	39.8%
Tf_Pn (40)	%BA Rem	38.5	3.6	31.2	45.8	13.9%
	Years Thin	3.48	0.43	2.61	4.35	23.6%
SM (55)	%SD Rem	55.8	3.4	49.1	62.5	25.7%
	Years Thin	5.13	1.00	3.12	7.15	12.8%
	AI*	0.55	0.06	0.43	0.67	10.2%
T (69)	%SD Rem	47.2	3.1	41.0	53.5	36.0%
	Years Thin	6.52	1.03	4.46	8.58	15.6%
	P	710.5	78.8	553.1	867.7	7.2%
	T	13.1	0.73	11.6	14.6	8.5%
	AI	0.56	0.07	0.42	0.69	11.1%
	Age *	47.4	4.15	39.1	55.7	8.5%
SF (57)	%SD Rem	52.6	4.3	44.1	61.2	21.0%
	P	1059.9	87.3	884.9	1235.0	13.7%

evapotranspiration (ET) over long periods (Peters, 1994). Surface runoff, subsurface flow, and groundwater flow typically add to the streamflow with various temporal and spatial scales rates. Thinning may affect all these flow components with a mainly increased amount (del Campo et al., 2019a).

A literature query on thinning, runoff, and streamflow terms would bring more than 2000 papers in a global scientific database. However, not all papers are relevant, and there is not enough coverage of Africa, Asia, or even Europe. In this section on effects of thinning on streamflow, we reviewed 60 papers that included experimental results of streamflow at catchment or plot scales. Recently, modelling studies became more abundant and accounted around 20 percent of the whole thinning-streamflow focused studies we reviewed. Therefore, the results or suggestions are based on the existing scientific knowledge that includes all kind of methodologies but do not cover all ecological environments. Arguably, North America is the only geographical region that has been subject to research on runoff/streamflow response to thinning at several ecosystem types and inclusion of various hydrological variables (water yield, surface runoff, high and low flows etc.). On the other hand, there has been a substantial increase in forest and streamflow studies in Japan for the last decade (i.e. Komatsu et al., 2011a, 2011b; Sun et al., 2017a, 2017b; Kubota et al., 2018).

Our review suggested that thinning generally increased streamflow. The streamflow response to the thinning treatments is an increase in water yield occurring promptly after forest cutting, with the magnitude proportional to the percentage reduction in basal area (BA). The paired catchment studies, around 30 percent of the whole set of papers we reviewed, provided a detailed monthly comparison on the post treatment period. One of the documented findings were on the seasonality. The difference between the streamflow of the treated catchment and the control depended significantly on the precipitation and ET conditions. The streamflow increase is more detectable or visible in rainy months especially in case of broadleaved forest ecosystems (Serengil et al., 2007). The duration of the streamflow increase, that is the case in almost all studies reviewed, goes on between 2 and 10 years based on the thinning intensity, stand attributes, and the ecologic conditions. The critical determinant is the regrowth rate of the ecosystem under consideration. Furthermore, some studies reported that the streamflow increase after the thinning may reverse if the vegetation regrowth is triggered enough (i.e., Lane and Mackay, 2001) or if repeated thinning treatments are not implemented.

To understand the streamflow response to a thinning, it might be good to first concentrate on the partitioning of water reaching the forest floor (see previous sections) and subsurface and ground flows (next section). Consequently, physical conditions of the plots for thinning (i.e., slope, aspect, soil, climate), intensity of thinning, and the way of thinning operation (i.e., skidding, tractors) may affect the surface runoff processes. All these variables that require field observations should be considered in assessing the effects of thinning on runoff and streamflow. Some studies reported large variations in the responses of streamflow or streamflow components to thinning treatments. For example, Moreno et al (2016) suggested that forest thinning may lead to a less stable hydrologic system in some cases, that variations in mean and extreme events are larger, particularly in the rainy winter season. It was also the case after a 50 percent thinning of steep headwater catchments (Sun et al., 2017a, 2017b), in which over 30 mm rainfall and around 2 mm/h rainfall intensity caused significant flow peaks and flow rises. It is likely that the streamflow may still increase not with surface runoff but subsurface or groundwater flow (Callegari et al., 2003) to enhance dry season flows. If the treatment is performed with minimum disturbance to the forest floor, the effects on peak flows would be minimal, as underlined by Kuraji et al (2019).

Our review also highlights that climate variability (inter-annual or intra-annual) played an important role in streamflow responses to thinning. A rainy winter season or drought may affect the streamflow response significantly. An ample soil water storage would reduce the sensitivity of the streamflow to fluctuations in precipitation and therefore thinning (Vose et al., 2016). The drought conditions might offset the extra runoff produced by thinning (Robles et al., 2014). In other words, thinning can promote resilience to drought effects. Another point to consider is the duration of the runoff increase after the thinning. The recovery of the crown closure would be slower in cooler climates or poor regeneration conditions (Lane and Mackay, 2001). Some studies in boreal forests showed earlier accumulation, melt, and disappearance of snow in young, thinned stands compared to un-thinned (Winkler and Roach, 2005).

Because the streamflow response to thinning is dependent upon various factors, management decisions on thinning treatment for water benefits must consider local conditions and future climate change impacts. The currently accumulated scientific knowledge in many world regions is still insufficient to develop robust management strategies on the thinning-streamflow relationship, and more research is needed.

4.2. *Groundwater*

Groundwater is an important water component and accounts for the majority of low flows or base flows. Research into assessing the effects of thinning on groundwater is limited, and only a dozen published studies are found in the literature, among which the majority focused on hydrological responses with inclusion of the groundwater component. In addition, groundwater table change or deep infiltration is often used as a proxy to reflect responses of groundwater resources. The thinning effects on groundwater are generally positive as thinning reduces canopy interception and consequently makes more water available for deep percolation (Garcia-Prats et al., 2018; del Campo et al., 2014, 2019a; Knoche, 2005), groundwater recharging (Moreno et al., 2016) and increasing of groundwater tables (Jutras et al., 2006; Stoneman, 1993; Ruprecht et al., 1991). A recent modeling study by Momiyama et al. (2021) showed that more pronounced beneficial effects on low flows can be promoted if thinning is done in the watersheds with higher water retention capacities where groundwater can be more effectively recharged.

However, if thinning intensities are not sufficiently large, groundwater responses may be limited. For example, Surfleet et al. (2020) found no measurable difference in depth to groundwater or soil moisture following the upslope forest thinning, likely due to the low level of forest removal with 2.8 m^2/ha reduction of the forest BA. Additionally, the groundwater responses are relatively shorter-term and more variable as the remaining trees grow faster and larger after thinning. For example, Lane and Mackay (2001) found that total annual streamflow increased 31% for the first 4 years; then returned to the pretreatment level in the subsequent 4 years; and changes in base flows were primarily responsible for the streamflow increases in a mixed-species eucalypt forested catchment in Australia. Stoneman (1993) reported the deep groundwater level at a midslope location increased by 8 m and at a valley location by 4 m in the 8 years after thinning. In contrast, Moreno et al. (2016) showed that thinning might even cause some adverse hydrological effects such as reduction in snow water equivalent (SWE) when seasonal hydrological effects are examined and decreasing vadose zone moisture if thinning causes soil compaction.

4.3. *Water use efficiency*

Thinning can reduce competition between individual trees and thus promote the growth and water use of remaining trees. Because forest carbon and water are important ecological functions sensitive to environmental change and human interventions, their coupling, often represented by water use efficiency (the ratio of carbon assimilation to water consumption of vegetation, WUE), has been receiving a growing attention in ecohydrological studies (Gentine et al., 2019; Wang et al., 2019a, 2019b). WUE is often defined in different ways at different spatial scales (leaf-level, tree-level, stand-level or even landscape level) (Giles-Hansen et al., 2021; Keenan et al., 2013). Different definitions at various spatial scales make it difficult to conduct comparisons among studies. In assessing how thinning may affect WUE, researchers often use DBH increment divided by transpiration (sap flow) to define WUE at both individual tree- and stand- levels as these two parameters are relatively easily collected. In addition, WUEi (intrinsic WUE, which is the ratio between net carbon assimilation in photosynthesis and stomatal conductance) is often estimated with isotope data or experimental methods.

A dozen of research on thinning and WUE were only conducted in the past two decades. Because thinning can increase both tree growths and water use (transpiration), its effects on WUE largely depend upon relative incremental rates of these two variables. In general, thinning increased WUE (Gavinet et al., 2019; Fernandes et al., 2016; Forrester et al., 2012), and these positive effects are even more pronounced in more heavily thinning treatments (Niccoli et al., 2020; Park et al., 2018; Wang et al., 2019a, 2019b) or under the drought conditions (Wang et al., 2019a, 2019b). However, Dore et al (2012) showed that thinning effects on WUE are minor and short-lived in the ponderosa pine forest ecosystem. Wang et al. (2019a, 2019b) also noted that thinning did not change WUE in the average year, but significantly increased WUE in the drought year in their study in young and dense lodgepole pine forests in the Southern interior of British Columbia, Canada. In spite of inconsistent results, thinning can significantly mediate the drought effects through increasing WUE (Gavinet et al., 2019; Wang et al., 2019a, 2019b). This has important management implications for designing future climate change mitigation strategies.

WUEi responses to thinning treatments are also assessed. The results include no significant responses (Martín-Benito et al., 2010; McDowell et al., 2006), positive responses (Niccoli et al., 2020; Park et al., 2018) and negative responses (Wang et al., 2019a, 2019b; D'Alessandro et al., 2006; McDowell et al., 2003). Based on these limited studies (about a dozen), the results on WUEi responses to thinning treatments are more variable and even contradictory as compared with the results on WUE. One of the possible reasons for these inconsistent results is usage of different research methods (i.e. isotopic signatures of tissues, field measurements of gas exchanges) (Wieser et al., 2018). Consequently, further research is needed to draw general conclusions and advance the theories and mechanisms that govern WUEi variations in changing environments.

4.4. *Water quality*

Our review detected 23 documents where the terms “thinning” and “water quality” were mentioned together. Forest stands of the revised studies significantly varied, but all tested the effects of thinning intensities between 10% and 50% of stand density removed. Most of the identified studies were done in conifer stands, either natural (such as the ones in central Europe; Hubbard and Lowrance, 1997; Bäumler and Zech, 1997, 1999; Knoche, 2005; Chu et al., 2019) or planted, mostly from Japan (Chiwa et al., 2020; Fukuyama et al., 2010; Hotta et al., 2007; Shinomiya et al., 2020; Oanh et al., 2021) but also from Europe (Shah et al., 2021) and South America (Perrando et al., 2021). Research studies in broadleaf stands were also identified (Fernández et al., 2011; Serengil et al., 2007; Gökbulak et al., 2008). These documents showed that, while the specific changes caused by thinning varied on-site conditions, there are some common trends. First, thinning could cause an increase in acidity and ion loads and suspended sediments (Baümler and Zech, 1999; Serengil et al., 2007; Shinomiya et al., 2020), and temperature (Oanh et al., 2021; Roon et al., 2021) in water. However, such changes are usually of smaller magnitude than removing all the tree cover (clearcutting) (Hubbard and Lowrance, 1997; Fernández et al. ,2011).

In addition, when water quality is modified, such changes are temporal, usually being limited to 1–2 years after thinning (Baümler and Zech, 1999; Shinomiya et al., 2020). However, a similar number of manuscripts reported no changes after thinning in water quality. Such a lack of differences was explained mostly by two mechanisms. First, low-impact forestry operations can be effectively implemented to avoid significant changes in water quality after thinning (Gökbulak et al., 2008; Hotta et al. ,2007; Shinomiya et al., 2020; Shah et al., 2021), such as avoiding machinery wheel ruts, decommissioning forest roads after the operations and using thinning slash to cover bare mineral soil. Second, increased understory growth following higher canopy openness due to thinning can counteract management impacts (Knoche, 2005; Fukuyama et al., 2010; Chu et al., 2019; Chiwa et al., 2020) by reducing runoff and preventing soil particles from reaching the streams. In addition, it has been recorded that maintaining a strip of riparian forests could also be enough to prevent thinning impacts on water quality from affecting forest streams (Hubbard and Lowrance, 1997). All this evidence indicates that most of the moderate modifications in water quality caused by thinning operations can be reduced by careful operational planning.

5. Ecohydrological implications of thinning for adaptive forest management

The results obtained in this review allowed us to draw some conclusions towards global ecohydrological implications of forest management. Here we address all hydrological effects of thinning in a systematic context discussing their tradeoffs as they really affect management decisions. Beyond the summarized effects of the processes in the narrative review, the statistical approach performed for rainfall partitioning (RP), soil moisture (SM), stand transpiration (T) and sap flow (SF) can be further used to quantitatively explore the ecological and technical implications of thinning on the water cycle. The intensity of the treatment, one of the most critical technical aspects of thinning, must contemplate a threshold of 50% of tree removal (between 40 and 60% considering the 95% confidence intervals in Table 4) to unleash the significant effects reported here. Also noted here, this impact was more important when removing a high fraction of density in juvenile overstocked pine stands, where the processes of SM, T and SF presented a considerably higher impact for the treatment (the values in the thinned treatment were 1.34, 0.21 and 1.73 the value of the control for SM, T and SF respectively). This is likely due to the differences in both anatomical (proportion of sapwood, and higher sapflow per unit of sapwood) and physiological traits (faster growth rate) of young conifers as compared to mature forests (Perry and Jones, 2017). The time elapsed since cutting that an effect lasts is another important criterion for planning and decision-making in forest management. In this case, a range of 3 to 8 years (95% of confidence intervals in Table 4) can be approximated, where canopy closure following thinning recovers first given the availability of resources and space for the remaining trees and hence the effects on net precipitation are of shorter duration (between 2.6 and 4.3 years). On the other hand, the soil water surplus enhanced with thinning persists for longer with a parallel effect on T (and likely on the other hydrological processes not meta-analyzed) that can be set between 4.5 and 8.6 years (Table 4 and Fig. 5). These results would suggest different recurrence periods for thinning depending on the hydrological process targeted in forest-water management, which can have an impact on the efficiency of management and project's resources allocation (e.g., water provision, climate resilience, etc.).

The technical aspects of forest-water management are modulated by climate, with hot/warm climates showing a larger effect size of thinning (Csa, Csb, Cfb) whilst drier climates offsetting these effects. An aridity index above 0.55 (95% CI $\approx$ 0.42–0.68) seems to enhance the effects of thinning on either SM or T and the corresponding Pg threshold for the significant effect of thinning in T is 550–868 mm (Table 4 and Fig. 5). On the other hand, the enhancement of SF with thinning (and hence on tree vigor and productivity) is achieved until a top threshold of 884–1235 mm (95% CI for Pg in the SF model Table 4 and Fig. 5). This result would make reasonable the use of thinning in the drier forests in order to mitigate climate change impacts. This evidence shows that thinning can reinforce resilience to drought, and hence, it would be particularly applicable in areas experiencing forest dieback and frequent drought effects due to climate change.

These values are obviously global averages (given the broad scope of the studies reviewed) and must be cautiously interpreted according to local conditions for management decisions. However, they can be used as a benchmark in order to assess and compare the impacts of thinning under any particular combination of biophysical and technical means. On the narrative side, good operational practices that protect soil and prevent erosion are sufficient in most cases to avoid the significant adverse effects of thinning on water quality and groundwater recharge. Some biases in our results could be related to the low sample size (as mentioned earlier), the specific biogeographical conditions of the reviewed studies, and the approach performed in this work. The strongest evidence of the thinning effects in the different processes addressed here is for the T, a process that combined the largest sample size and a homogeneity in the results reported in the literature (i.e., mm).

6. Conclusions and research gaps identified

Combining narrative review and the meta-analysis allowed us to draw some conclusions on the effect of thinning on hydrological processes in global forest ecosystems. The statistical results confirm our hypothesis on the thinning effects on RP, SM, T, and SF. In addition, the mean effect sizes of forest thinning on the surveyed hydrological processes have been quantitatively determined, and the variations of results have been analyzed among and within studies. We conclude that the global averaged thresholds (40–60%) on the significant hydrological responses to thinning intensities and the thinning intervals (3–8 years) required for sustaining significant hydrological effects do exist. Our results strongly demonstrated that thinning can be an effective mean for remaining trees to cope with climate change impacts (i.e. frequent droughts and wildfires), as thinning provides a more hydrated forest system. However, there are large variations in hydrological responses to thinning subject to climate, local site conditions and thinning operations. Thus, management decisions on thinning require consideration of various factors in a systematic context as well as tradeoff analysis among various management objectives.

Our review also identified some critical research gaps. Firstly, there is a need to report full results (mean, standard deviation and sample size) of the processes in the most and consistent units used in forest hydrology and ecohydrology, i.e., mm (Streamflow, RP, ET, T), volumetric content (SM), liter/tree (SF), and in a suitable hydrologically meaningful timestep (day, growing season, year). These consistent units should greatly facilitate more meaningful comparisons and future review studies in more systematical way. Secondly, there are critical research gaps in groundwater, ET, streamflow and water quality in the global forest ecosystems, but boreal forests in particular. Finally, when planning a forest intervention such as thinning, there is a need to assess and manage ecohydrological effects in the context of various other services such as biodiversity, carbon, fire risk and nutrient balance. Hence, a more explicit effort on quantitatively translating the hydrological effects of thinning into drought resistance, fire risk reduction, or watershed resilience to climate change is likely the next global challenge for ecohydrology-based forest management. Any long-term research and monitoring on the ecological effects of thinning can greatly support robust results and management decisions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2022.120324.

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Table SM1. Summary of the significant models fit with for both the hydrological processes without moderators (random-effects models) and with moderators (mixed-effects models). The hydrological Processes are Stemflow (Sf), Throughfall (and Net Precipitation) (Tf_Pn), Soil Moisture (SM), Total ET (ET), Stand Transpiration (T) and Tree-level water use (SF). τ2 is the the amount of heterogeneity; I2 and, H2, are statistics for the amount of heterogeneity; Q is the test for heterogeneity; df is the degrees of freedom; R2 is the explained heterogeneity by the moderator; Q_M is the omnibus test of moderators; and p the p-value. %BA Rem: Thinning Intensity (% of basal area removed); % SD Rem: Thinning Intensity (% of stand density removed); Years Thin: Years elapsed since thinning; P: Mean annual precipitation (mm); T: Mean annual temperature (ºC); AI: Aridity Index; Period: Period of monitoring; Clim: Climate type (Köppen–Geiger); Forest: Forest type; Species: Main Species.

Hydrol. Process	**τ^2**	**I^2 (%)**	**H^2 (%)**	**R^2 (%)**	**Q**	**df**	**p**	**Q_M**	**df**	**p**
Sf, No mod.	**0.7596 (SE = 0.3453)**	**97.2**	**36.41**		**377.6**	**11**	**< .0001**			
Tf_Pn No mod.	**0.0213 (SE = 0.0067)**	**92.3**	**13.04**		**470.8**	**39**	**< .0001**			
Period	0.0197 (SE = 0.0063)	91.8	12.2	7.5	441	38	< .0001	41.5	2	< .0001
%BA Rem	0.0179 (SE = 0.0059)	90	10	16	346.4	38	< .0001	6.2	1	0.0129
%SD Rem	0.0189 (SE = 0.0061)	90.6	10.6	11	342.7	38	< .0001	4	1	0.0465
Climate	0.0166 (SE = 0.0060)	87.1	7.75	22.1	247.9	34	< .0001	56.8	6	< .0001
Forest	0.0211 (SE = 0.0069)	91.8	12.23		449.7	37	< .0001	40.1	3	< .0001
Species	0.0183 (SE = 0.0062)	90.2	10.22	14.1	398.7	36	< .0001	48.7	4	< .0001
SM, No mod.	**0.0254 (SE = 0.0063)**	**96.5**	**28.2**		**1808**	**54**	**< .0001**			
Period	0.0259 (SE = 0.0066	96.3	27		896	51	< .0001	30	4	< .0001
%BA Rem	0.0209 (SE = 0.0054)	95.4	21.6	17.7	1550	53	< .0001	12.4	1	0.0004
%SD Rem	0.0192 (SE = 0.0050)	95	19.9	24.6	1357	53	< .0001	15.6	1	< .0001
Years Thin	0.0220 (SE = 0.0056)	95.7	23.1	13.4	1562	53	< .0001	8.4	1	0.0037
Clim	0.0195 (SE = 0.0056)	94.5	18.2	23.2	652	45	< .0001	54.8	10	< .0001
Forest	0.0261 (SE = 0.0067)	95.9	24.6		993	51	< .0001	29.4	4	< .0001
Species	0.0236 (SE = 0.0061)	95.8	23.7		855	51	< .0001	36.6	4	< .0001
ET, No mod.	**0.0362 (SE = 0.0169)**	**89**	**9.13**		**111.2**	**19**	**< .0001**			
T, No mod.	**0.3469 (SE = 0.0630)**	**99**	**99.8**		**5681.6**	**67**	**< .0001**			
Period	0.3466 (SE = 0.0639)	99	98.3	0.1	5647.1	65	< .0001	51.2	3	< .0001
%BA Rem	0.2261 (SE = 0.0423)	98.5	64.4	34.8	3945.3	66	< .0001	35.4	1	0.0008
%SD Rem	0.2306 (SE = 0.0431)	98.5	64.9	33.5	4400.8	66	< .0001	34	1	0.0008
Years Thin	0.2883 (SE = 0.0533)	98.8	82.2	16.9	4331	66	< .0001	13.3	1	0.0002
P	0.3250 (SE = 0.0597)	98.9	92.3	6.3	4944.8	66	< .0001	5.1	1	0.0243
T	0.3137 (SE = 0.0577)	98.9	88.5	9.6	5667.1	66	< .0001	7.1	1	0.0078
AI	0.3084 (SE = 0.0568)	98.9	87.7	11.1	4898	66	< .0001	8.7	1	0.0032
Climate	0.2082 (SE = 0.0415)	98.2	53.9	40	3009.9	58	< .0001	129	10	< .0001
Forest	0.3624 (SE = 0.0673)	99	98	0.1	5364.7	64	< .0001	47.4	4	< .0001
Species	0.3598 (SE = 0.0668)	99	97.7	34.8	4793.4	64	< .0001	48.1	4	< .0001
SF, No mod.	**0.1670 (SE = 0.0355)**	**99.4**	**155.5**		**5391.5**	**56**	**< .0001**			
Period	0.1724 (SE = 0.0371)	99.3	144.6		4543.1	53	< .0001	57.7	4	< .0001
%BA Rem	0.1444 (SE = 0.0313)	99.2	121.9	13.5	5368.7	55	< .0001	8.6	1	0.0034
%SD Rem	0.1328 (SE = 0.0290)	99.2	118.4	20.5	5212.3	55	< .0001	13.7	1	0.0002
P	0.1470 (SE = 0.0319)	99.2	119.9	12	3828	55	< .0001	7.8	1	0.0053
Climate	0.1481 (SE = 0.0347)	99.2	126.3	11.3	3224.5	48	< .0001	79.9	9	< .0001
Forest	0.1717 (SE = 0.0371)	99.3	134.4		3851.5	54	< .0001	57.9	3	< .0001
Species	0.1673 (SE = 0.0365)	99.3	132.8		3585.6	53	< .0001	61.3	4	< .0001

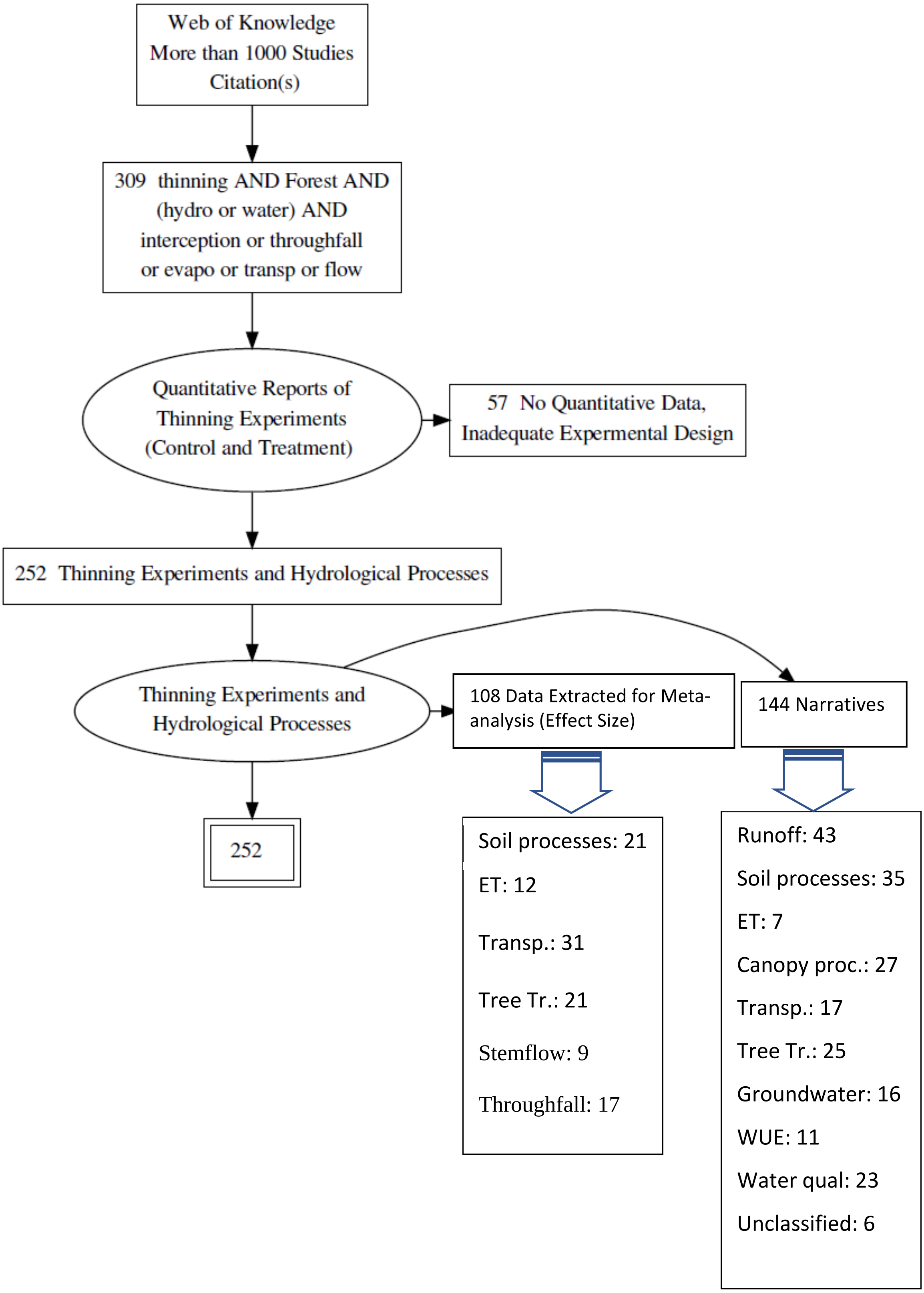

Figure SM1. Graphical representation of the flow of citations reviewed in this systematic review (PRISMA flow diagram, http://prisma.thetacollaborative.ca). Note: Totals do not always equal the sum of the papers in each cell because many studies assessed multiple response metrics.

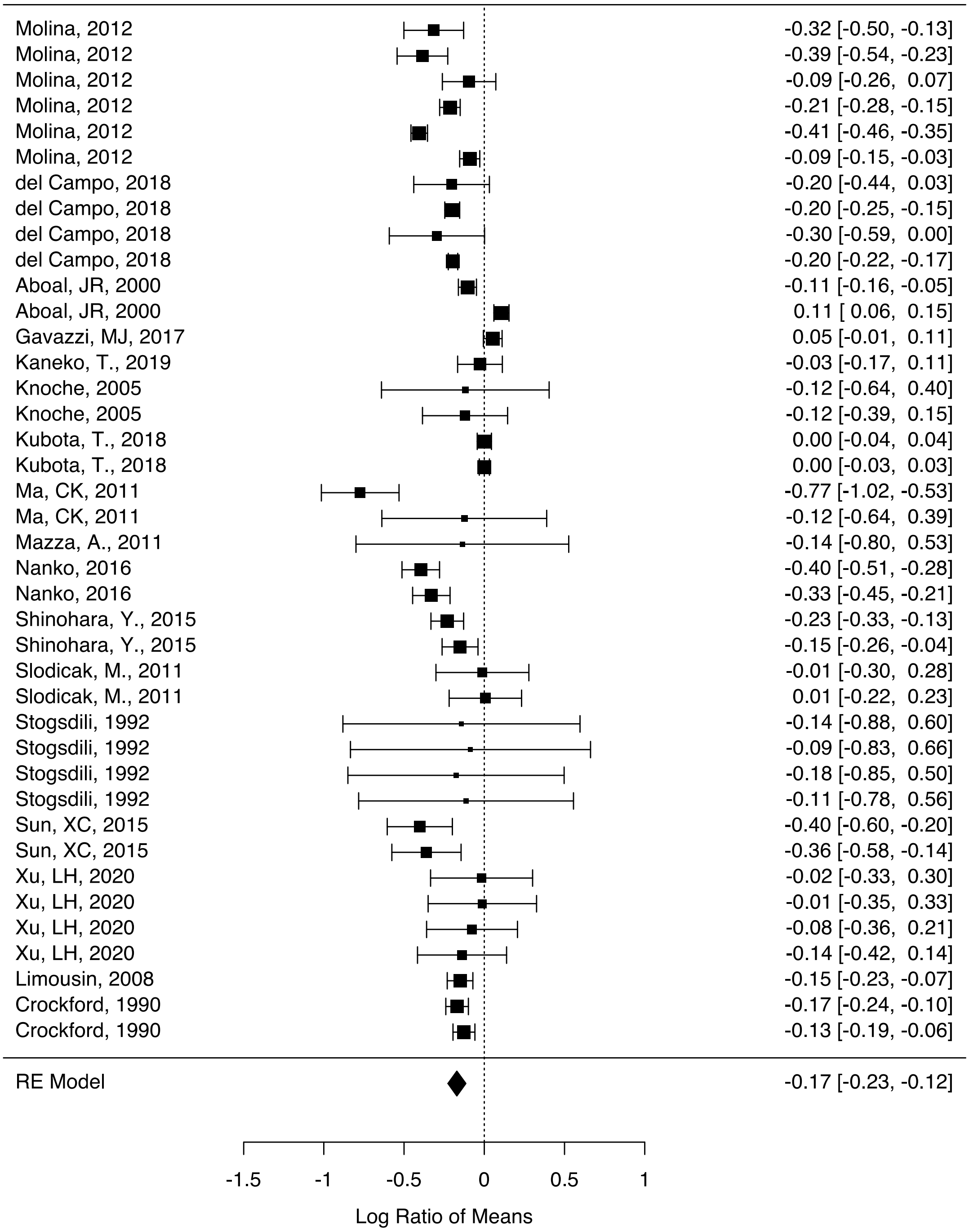

Figure SM2: Forest plot of the results of the 40 records from 17 studies examining the effect of thinning on Throughfall (and Net Precipitation). The plot illustrates the ln (RoM) of control over the thinning treatment (effect size) with corresponding confidence intervals (95%).

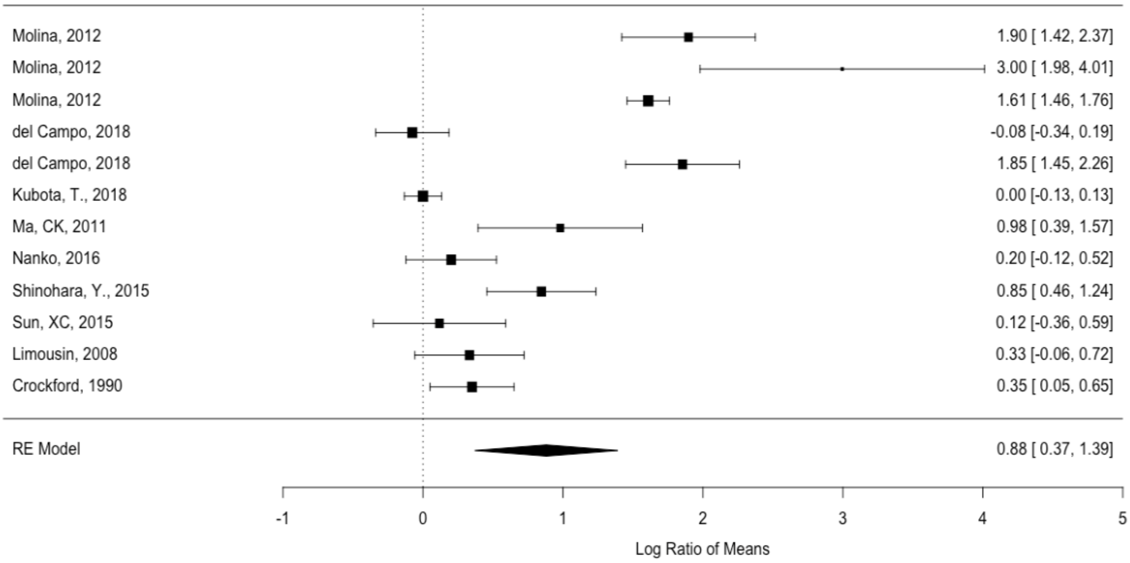

Figure SM3: Forest plot of the results of the 12 records from 9 studies examining the effect of thinning on Stemflow. The plot illustrates the ln (RoM) of control over the thinning treatment (effect size) with corresponding confidence intervals (95%).

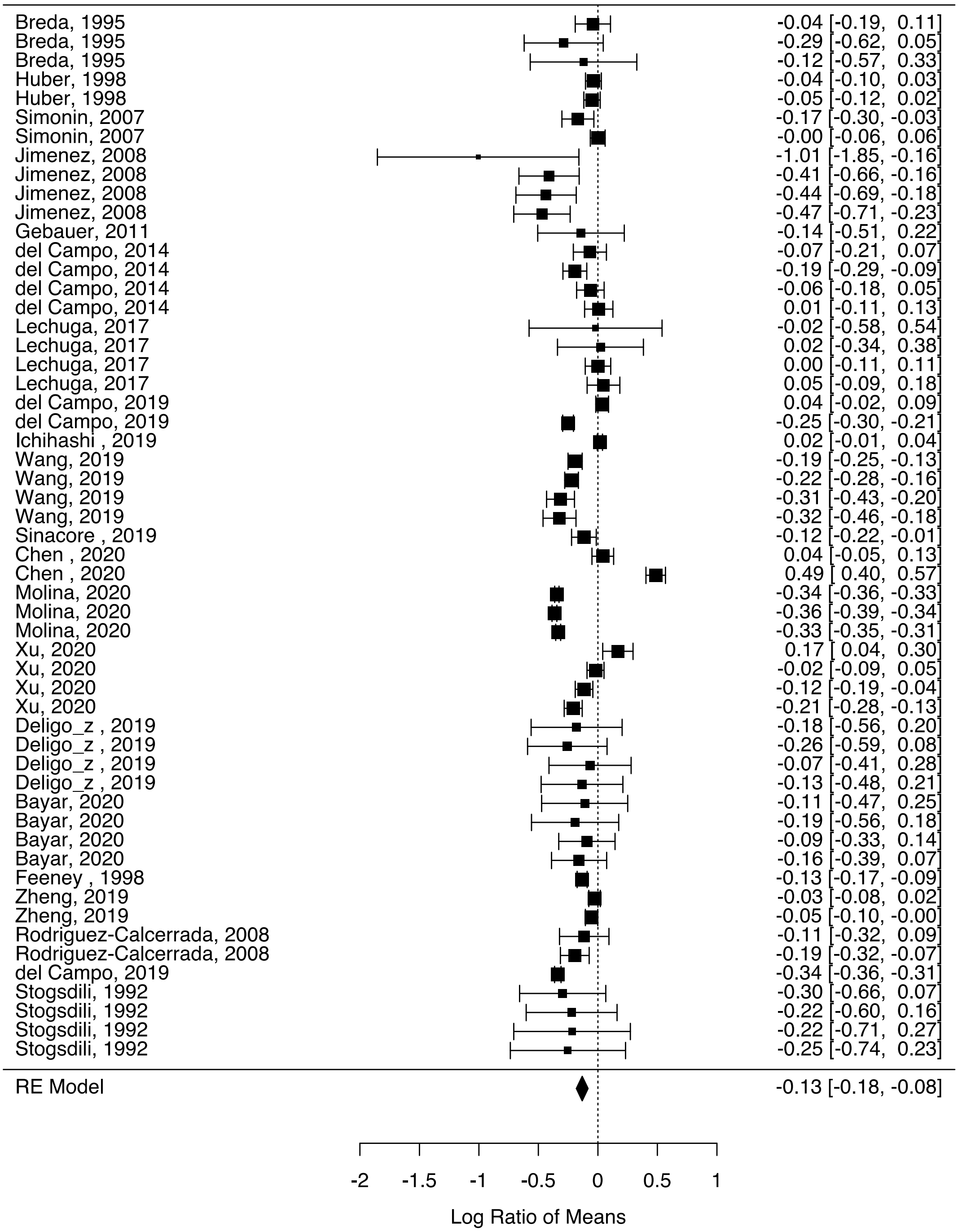

Figure SM4: Forest plot of the results of the 55 records from 21 studies examining the effect of thinning on Soil Moisture. The plot illustrates the ln (RoM) of control over the thinning treatment (effect size) with corresponding confidence intervals (95%).

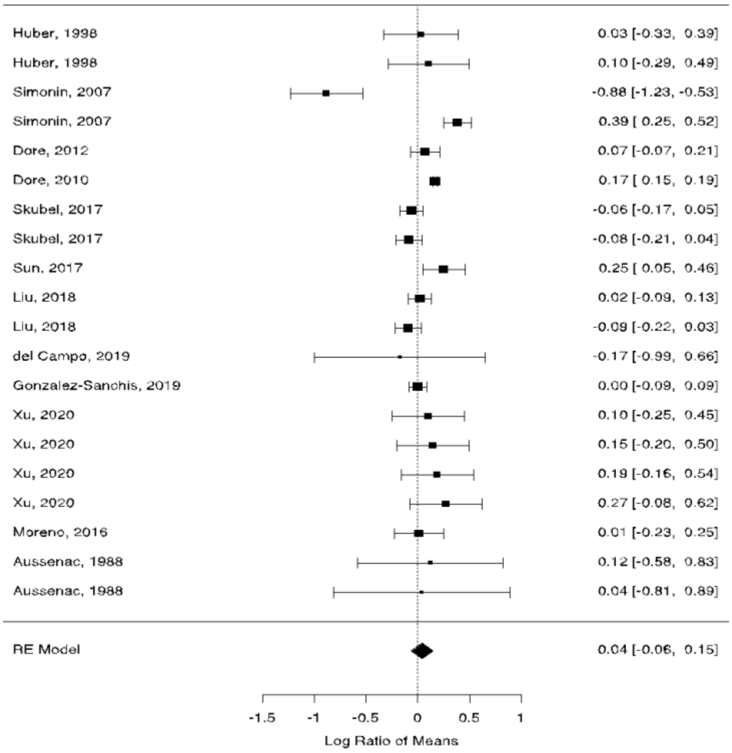

Figure SM5: Forest plot of the results of the 20 records from 12 studies examining the effect of thinning on Total ET. The plot illustrates the ln (RoM) of control over the thinning treatment (effect size) with corresponding confidence intervals (95%).

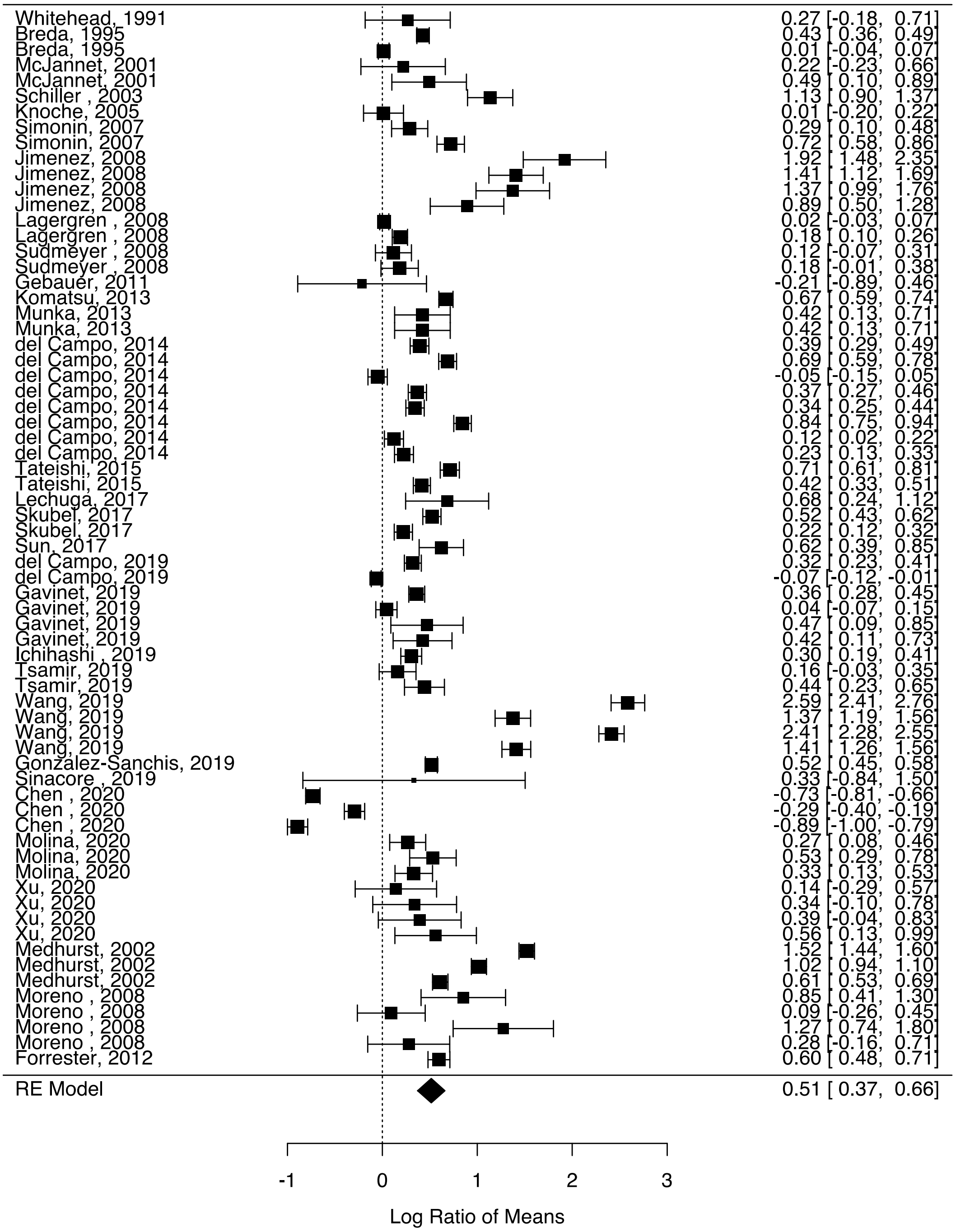

Figure SM6: Forest plot of the results of the 68 records from 31 studies examining the effect of thinning on Stand Transpiration. The plot illustrates the ln (RoM) of control over the thinning treatment (effect size) with corresponding confidence intervals (95%).

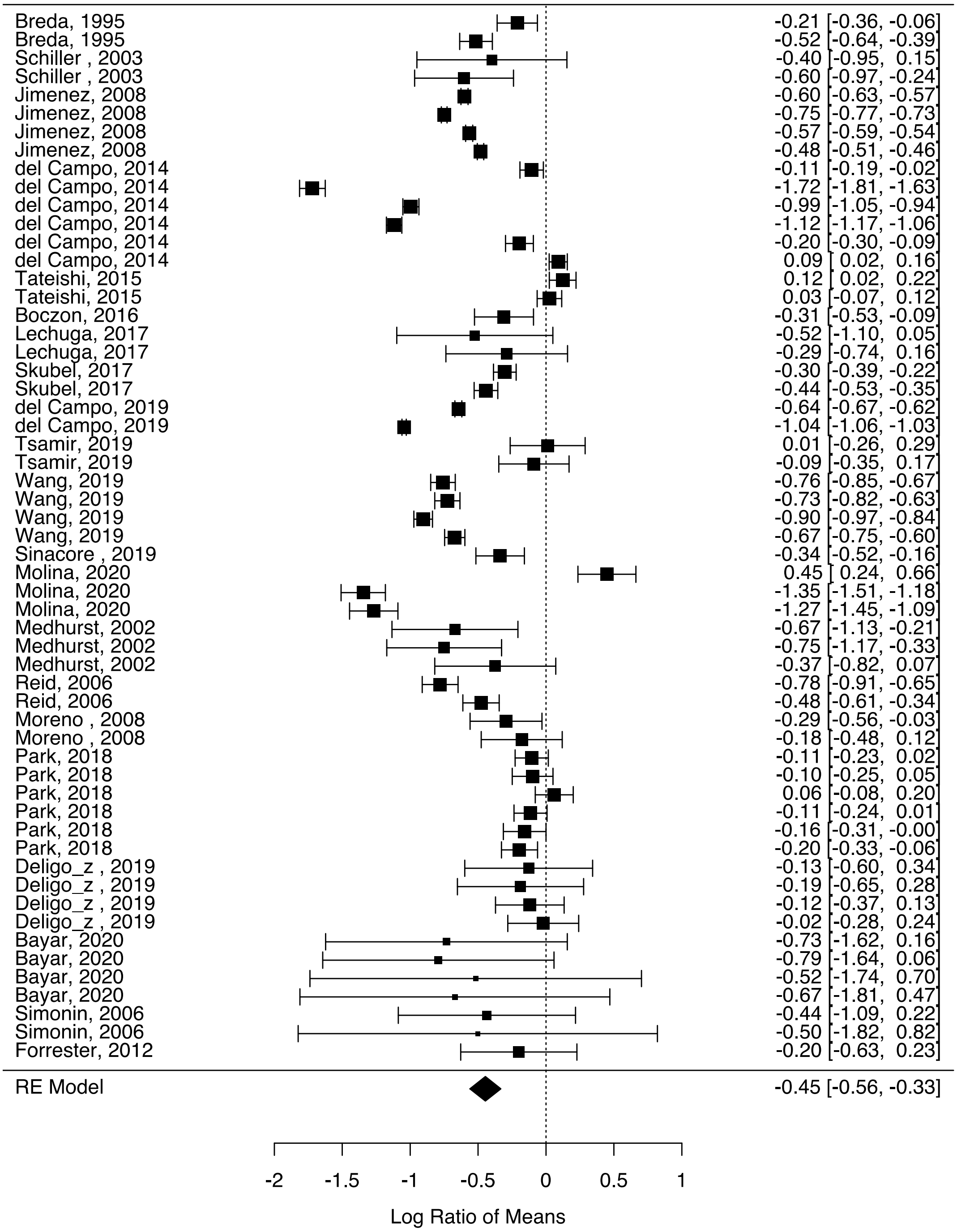

Figure SM7: Forest plot of the results of the 57 records from 21 studies examining the effect of thinning on Tree-water use. The plot illustrates the ln (RoM) of control over the thinning treatment (effect size) with corresponding confidence intervals (95%).

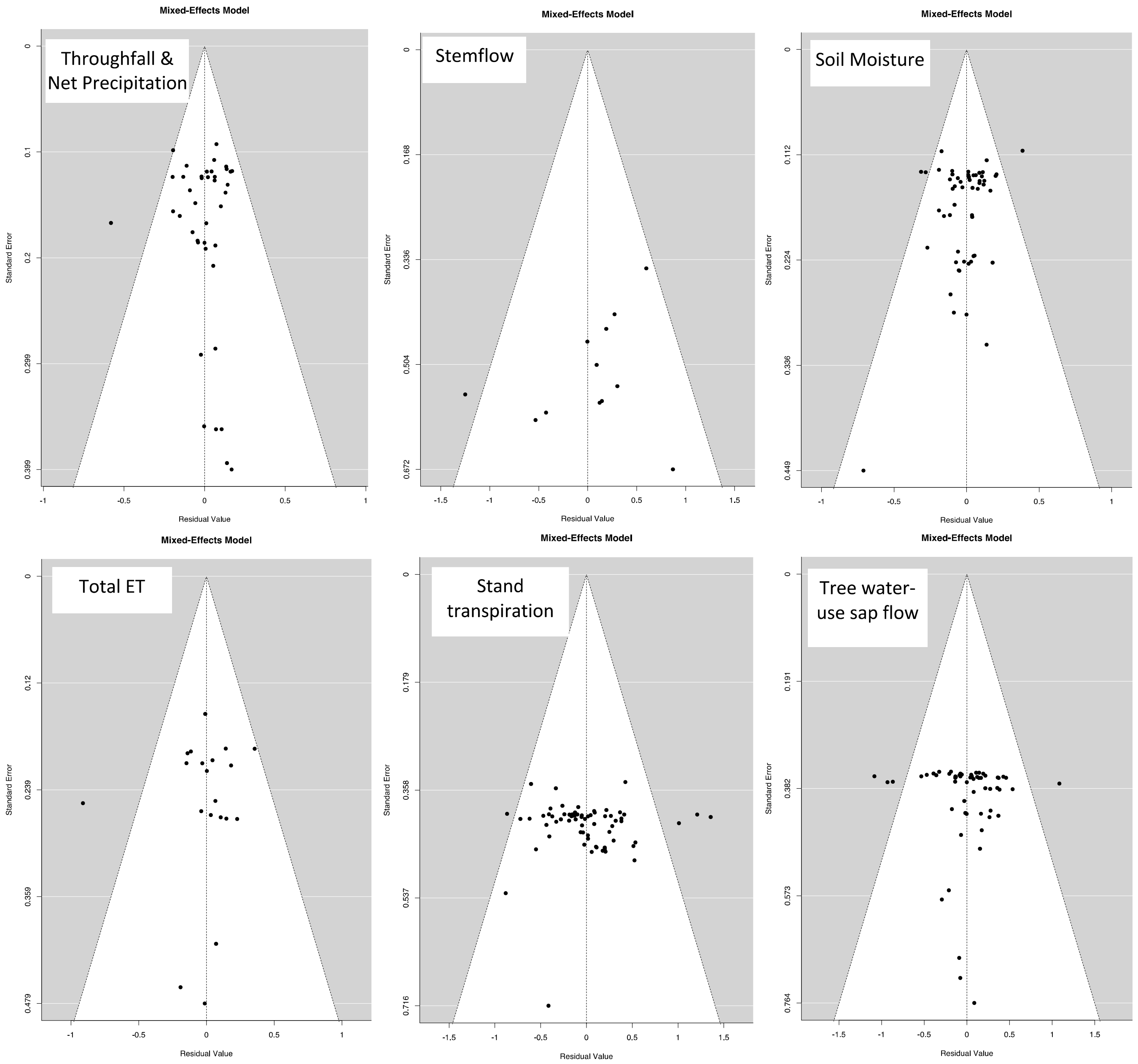

Figure SM8: Funnel plot for the different hydrological processes meta-analyzed for mixed-effect models including thinning intensity (% of SD removed), years elapsed since thinning aridity index as moderators. The plot illustrates the residuals on the X axis against their corresponding standard errors. A vertical line is drawn at zero with a pseudo-confidence interval region given by ±1.96 · SE.

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