SYLWAN 166 (6): 390-402, June 2022
https://doi.org/10.26202/sylwan.2022031
Journal homepage: https://sylwan-journal.pl

ORIGINAL PAPER

Effects of thinning methods on soil water resources and soil drought risk in Scots pine stands

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ABSTRACT

Climate change is leading to an increase in the frequency and intensity of droughts, posing a real threat to forest stands, for which lack of available soil water may limit growth and health. Many authors indicate that properly conducted forest management may contribute to increasing the resistance of stands to drought stress. One of the possibilities offered by forest management is the use of an appropriate thinning method. The aim of this publication is to show how different thinning methods affect soil water resources and the occurrence of soil drought. Model studies of the variability of soil water resources were carried out on the experimental plot in Kozienice Forest District, using meteorological data from 2011-2020 for 9 thinning treatments. These studies demonstrate that in the fresh conifer forest site, the most favourable conditions are created by moderate selective thinning, as well as a low level of thinning that does not permanently disrupt the canopy.

KEY WORDS

climate change, drought, forest management, pine forest, soil water storage

Introduction

Climate change is making drought an increasing threat to forest stands, with the expectation of warmer and drier weather during the growing season in Central Europe (Degirmendžić *et al.*, 2004; Briffa *et al.*, 2009; Dubrovsky *et al.*, 2009; Lindner *et al.*, 2010). As a result, evaporation from fields will increase and droughts will become more frequent, severe, and longer lasting (Allen *et al.*, 2010). Globally, there was an increase in the annual percentage of area with droughts over the period 1902-2008 (Wang *et al.*, 2014). Since 1970, the intensity and duration of droughts has increased and the area affected by droughts has increased (Burke *et al.*, 2006; Blunden *et al.*, 2011). In fact, it is thought that the 2018-2020 drought in Central Europe was likely the worst in 2000 years (Büntgen *et al.*, 2021). Drought stress is considered a major threat to tree vigour and growth, eventually leading to tree death (Allen *et al.*, 2010). Droughts in 2018-2019 have resulted in damage to or death of coniferous and hardwood stands across much of Europe (Braun *et al.*, 2020; Schuldt *et al.*, 2020).

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Received: 18 May 2022; Revised: 2 August 2022; Accepted: 31 August 2022; Available online: 7 October 2022

Thinning, *i.e.*, reducing stand density, may be one way for a forest to adapt to climate change (Misson *et al.*, 2003; Martin-Benito *et al.*, 2010). Many researchers indicate that thinning may be one of the main factors in increasing available soil water supply (Stogsdill *et al.*, 1992; Breda *et al.*, 1995; Baumler and Zech, 1997).

The objective of this study was to determine the effects of thinning methods on soil water balance and the number of days with soil water deficit as an indicator of drought stress risk.

Materials and method

History of the thinning experiment. The study was conducted on a plot in Kozienice Forest District, Chinów Sub-district, sub-compartment 100a, where pine seedlings were planted in 1965 in fresh coniferous forest on Brunic Arenosols. The Forestry District is located in the Central Polish Lowland. The experimental plots had a size of 16×36 m. In 1999-2001, a thinning trial was started on the plot.

The trial was set up with the following thinning treatments considering the planting commitment:

A (0.8 m square spacing). *Stabilizing group thinning*, the same number of plus trees were selected as before, increased by the number of trees growing in close proximity (in a biogroup) and considered plus trees Now referred to as *group thinning* (TG1).

B (square spacing 1.0 m). Included classical selection thinning, with plus trees selected at a rate of 500 trees per hectare. No more than one of the damaging trees was removed from the dominant layer for each of the plus trees. Currently referred to as *moderate thinning* (TU1).

C (square spacing 1.2 m). Designed for simplified heavy thinning (corresponding to the target trees), with trees selected at a rate of 350 plus trees per hectare. All competitors that came into contact with the crown were removed from their immediate vicinity. Currently referred to as *strong thinning* (TS1).

D (1.0 m triangular spacing). *Stabilizing group thinning*, with the same number of plus trees selected as before, increased by the number of trees growing in close proximity (in a biogroup) and considered plus trees. Now referred to as *group thinning* (TG2).

E (triangular spacing 1.2 m). *Classical selection thinning*, with plus trees selected at a rate of 500 per hectare. No more than one of the damaging trees, was removed from the dominant layer for each of the plus trees. Currently referred to as *moderate thinning* (TU2).

F (rectangular spacing 1.2×0.55 m). Designed for simplified heavy thinning (corresponding to the target trees), with trees selected at a rate of 350 plus trees per hectare. All competitors that came into contact with the crown were removed from their immediate vicinity. Currently referred to as *strong thinning* (TS2).

G (rectangular spacing 1.2×0.8 m). Treated as a control (without thinning); plus trees were determined for comparison only. Currently designated as *control* (K).

H (rectangular spacing 2.30×0.30 m). First sanitary cutting, then *moderate low thinning* (TUD).

I (square spacing 1.4 m). First sanitary cutting, then *moderate low thinning* (TUD).

The thinning of the plot was carried out in 1999 under the above assumptions. Later repetitions took place in 2007 and 2015. Biometric features of stands during the last measurement (year 2020) are presented in Table 1.

Modelling the water cycle in the plots of the thinning experiment. The water balance in the thinned plots was determined by modelling changes in daily soil water storage (SWS) in

Table 1.

Biometric features of stands in 2020. N = number of trees; G = breast height cross-sectional area; H = average height according to Lorey; D = average cross-sectional breast height; Hg = upper height (100 thickest trees per hectare); Dg – average breast height of the 100 thickest trees per hectare

Treatment	N [pcs ha^{-1}]	G [m^2 ha^{-1}]	H [m]	D [cm]	Hg [m]	Dg [cm]
A/TG1	1090	30.497	19.2	18.8	20.6	24.9
B/TU1	949	29.588	20.2	19.9	21.4	26.0
C/TS1	778	29.652	19.9	22.2	20.9	28.2
D/TG2	1019	30.952	20.1	19.8	21.3	25.9
E/TU2	931	28.868	20.0	19.9	21.2	26.1
F/TS2	802	24.513	19.7	19.8	20.7	25.1
G/K	1544	38.605	19.0	17.9	20.5	25.4
H/TD1	1087	35.651	19.2	19.9	20.5	26.2
I/TD2	1031	29.558	19.9	19.1	21.3	24.2
Average	1026	30.876	19.7	19.7	20.9	25.8

the profile to 100 cm depth, calculated from the difference in water supply by precipitation and water runoff by evapotranspiration:

$$SWS_{(i+1)} = SWS_{\mathrm{i}} + Th_i - EVT_i$$

where:

SWS – water storage,

i – day number,

EVT – daily evapotranspiration [mm],

Th – daily throughfall [mm],

$Th = P–I$

P – bulk precipitation [mm],

I – canopy interception [mm].

In accordance with the principles of water retention in the soil, the calculations were performed with the following boundary conditions:

(1) field water capacity, *i.e.*, the upper limit of the amount of water that can be retained in the soil; above this value, water drains from the profile.

(2) permanent wilting point, *i.e.*, the lower limit of the amount of water that occurs naturally in the soil.

Daily actual evapotranspiration (EVT) from forested areas was calculated using the Penman-Monteith formula:

$$\lambda EVT = \frac{\Delta(R_n - G) + \rho_a c_p \dfrac{VPD}{r_a}}{\Delta + \gamma(1 + \dfrac{r_s}{r_a})}$$

where:

R_n – net solar radiation,

G – soil outflow of heat,

Δ – slope of the saturated water vapour pressure curve,

λ – latent heat of vaporization,

γ – psychrometric constant,

P_a – density of air,

c_p – specific heat of air,
VPD – vapour pressure deficit,
r_a – aerodynamic resistance,
r_s – stomatal resistance.

Stomatal and aerodynamic resistance were calculated based on the variables that distinguish stands: leaf area index, ground cover and tree height. Tree height was measured using Haglöf Vertex IV.

Canopy interception (I) was calculated based on the Liu model for a precipitation series in which the water capacity of the tree canopy was determined using the Kondo model (Smax according to Komatsu *et al.*, 2008). Smax is directly related to the leaf area index of trees (LAI).

Leaf area index (LAI) and ground cover (GrnCov) were determined from hemisphere photos analysed using Hemiview software. Photos were taken at the centre of each variant of the thinning experiment. LAI and GndCov were determined for a stand bounded by a radius from the zenith (0.0°) to 52.5° of the hemisphere. This ensured that only the inventory in the considered variant of the experiment was measured.

The model studies were performed for meteorological data from 2011-2020. For the plot in Kozienice, the data of the Institute of Meteorology and Water Management were used, which are available at danepubliczne.imgw.pl from the station in Kozienice.

Model input parameters. Soil water properties were assumed for Brunic Arenosols based on the laboratory soil water properties curve (pF curve) established for the stand at the ICP-Forests permanent observation plot. The water resources in the soil profile at characteristic points are: field water capacity 209.81 mm, permanent withering point 31.80 mm, plant available water limit point 38.90 mm.

The stands that grew in certain variants of the thinning experiment were characterized by the features presented in Table 2.

The meteorological conditions during the 10-year modelling period are summarized in Table 3. In Kozienice, the greatest precipitation, exceeding 700 mm, occurred in 2017 and 2020, while the least precipitation, not exceeding 500 mm, occurred in 2019. The average air temperature reached values between 8.5°C in 2013 and 10.4°C in 2019.

Indicators to characterize the influence of thinning variation on soil water relations. To determine the variation of water resources in each treatment of thinning carried out, 3 indicators were used: (1) average annual soil water reserve, (2) the soil water reserve at the beginning

Table 2.
Characteristics of the stands in the variants of the thinning experiment

Variant	LAI	GndCov	Tree height [m]
A/TG1	1.444	0.548	20.6
B/TU1	1.229	0.537	21.4
C/TS1	1.224	0.507	20.9
D/TG2	1.239	0.526	21.3
E/TU2	1.116	0.482	21.2
F/TS2	1.351	0.494	20.7
G/K	1.321	0.552	20.5
H/TD1	1.200	0.497	20.5
I/TD2	1.209	0.542	21.3

of the growing season, which was assumed to be April 1, and (3) the number of days with limited water supply for plants.

Results

Daily soil water supply during the 10 year study period reached median values ranging from 138.1 mm in variant A to 181.7 mm in variant E. The differences between the SWS values obtained in the control and the other thinning treatments were statistically significant based on the Mann-Whitney U test, except for variant F (TS2). The non-parametric test was used because the distribution of daily SWS values was not normal. The mean annual soil water supply reached the highest values, >160 mm, in 2011, 2012, 2013, 2014, and 2017, with lower values in 2015, 2018, and 2020 and the lowest values in 2016 and 2019 (Table 4).

Compared to the control (G), lower average annual soil water resources were recorded in plot A with group thinning (TG1) and in variant F with heavy thinning (TS2), but in this case the difference was very small (Fig. 1a). The other thinning treatments had greater water resources than the control. Variant E with moderate thinning (TU2) had the highest mean annual soil water resources, more than 19 mm higher than the control (Fig. 1a). Based on the difference in

Table 3.
Meteorological parameters for the thinning experimental plots

Year	Precipitation [mm]		Daily temperature [°C]			Radiation [Wm^{-2}]		Air humidity [%]	Wind speed [sm^{-2}]
	Sum	Daily max.	Mean	max	min	Mean	max	Mean	Mean
2011	543.3	31.7	8.7	24.7	–14.1	108.7	309.3	79.1	2.82
2012	531.5	37.2	8.6	26.1	–20.7	113.9	317.9	79.2	2.84
2013	530.6	31.3	8.5	28.2	–15.9	108.6	417.9	79.5	2.73
2014	693.4	40.4	9.4	24.1	–15.5	102.1	309.4	80.0	2.66
2015	545.3	32.8	9.9	28.7	–9.3	111.0	358.3	74.7	2.67
2016	569.9	22.6	9.4	27	–14.8	107.0	374.2	77.7	2.47
2017	701.6	32.4	9.2	27.5	–17.1	104.2	326.2	78.0	2.66
2018	538.4	48.6	9.8	24.6	–14.6	126.9	372.4	76.3	2.42
2019	452.7	37.3	10.4	27.4	–8.2	124.3	397	74.6	2.63
2020	744.5	46.6	10.0	24.0	–2.6	103.2	294	75.3	2.47

Table 4.
Average annual soil water storage

Year	Experiment variant / Type of thinning									
	A/TG1	B/TU1	C/TS1	D/TG2	E/TU2	F/TS2	G/K	H/TD1	I/TD2	Average
2011	176.1	183.2	183.4	182.9	186.2	179.5	180.0	183.9	183.7	182.1
2012	146.4	173.3	174.4	172.2	183.8	161.5	163.0	176.1	175.3	169.6
2013	148.2	166.1	166.6	165.5	172.0	159.1	160.2	167.6	167.2	163.6
2014	176.5	192.8	193.5	192.2	198.0	186.2	187.0	194.4	193.8	190.5
2015	139.5	145.1	145.3	144.4	150.7	141.8	142.1	146.0	146.0	144.5
2016	104.1	123.6	125.6	120.8	147.1	111.4	111.5	129.2	127.6	122.3
2017	149.2	169.8	171.4	168.0	184.0	159.9	160.1	174.0	172.7	167.7
2018	120.6	141.8	142.6	140.6	153.5	129.1	131.2	144.3	143.8	138.6
2019	71.0	96.7	98.4	95.1	115.7	81.1	82.9	101.1	99.7	93.5
2020	134.0	151.8	153.2	150.9	162.3	143.2	143.7	155.0	153.4	149.7
Average	136.6	154.4	155.4	153.2	165.3	145.3	146.2	157.2	156.3	152.2

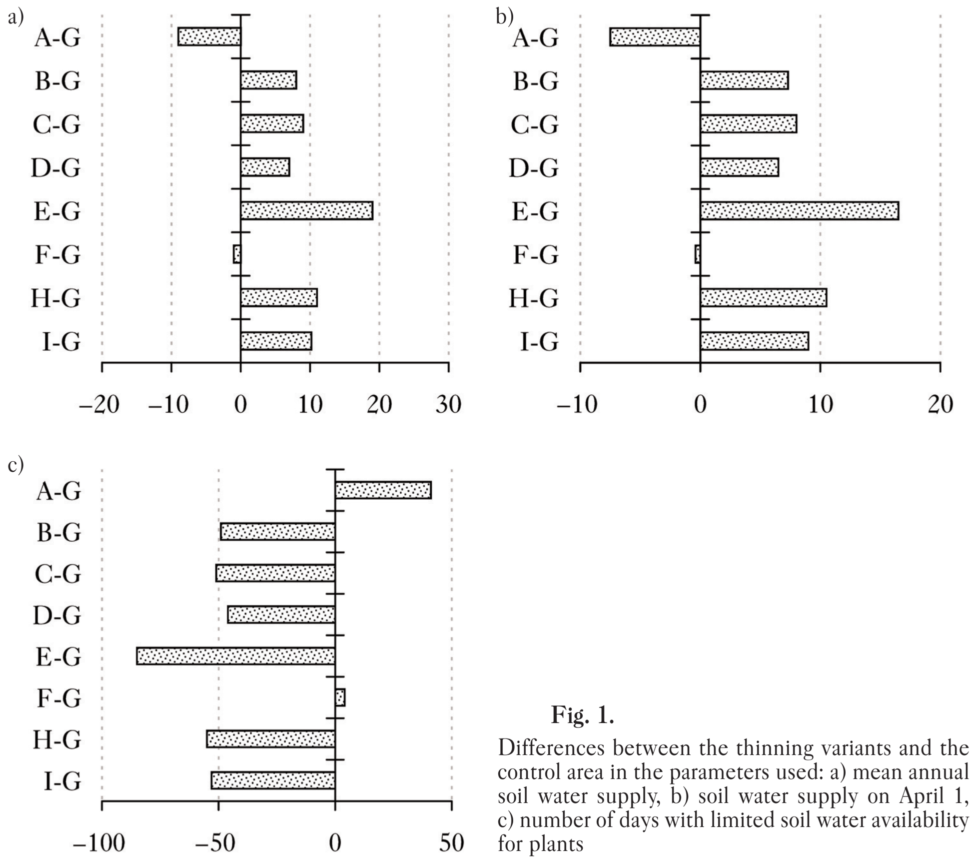

Fig. 1.
Differences between the thinning variants and the control area in the parameters used: a) mean annual soil water supply, b) soil water supply on April 1, c) number of days with limited soil water availability for plants

mean annual soil water resources compared to the control, the treatments can be ranked from worst to best in terms of soil water resources:

A(TG1) < F(TS2) < D(TG2) < B(TU1) < C(TS1) < I(TD2) < H(TD1) < E(TU2)

Based on climatic conditions in Central Europe, two distinct periods of water supply can be distinguished: the winter half-year (November-April) and the summer half-year (May-October), which together constitute the hydrological year. In the winter half-year, water resources are renewed because low temperatures, snow cover, and the absence of vegetation result in minimal evapotranspiration, while in the summer half-year the accumulated water is released. Thus, at the beginning of the summer half-year, which can be considered the beginning of the vegetation period, the water resources of the soil should be replenished to the maximum value, creating good conditions for the growth and development of vegetation after the winter break.

During the study period in the thinning plots, soil water reserves reached values close to the maximum at the beginning of the summer half-year in 2011, 2012, 2013, 2015, and 2018. In 2014, 2016, and 2017, it can be assumed that soil water saturation was sufficient. In 2019 and 2020 (Table 5), on the other hand, water reserves were low, which may have had a negative impact on crop growth conditions and increased the risk of soil drought in the following months. This indicator also shows that experimental variants A (TG1) and F (TS2) had lower average soil water reserves on April 1 than the control. The other treatments were higher, and the highest value was obtained in variant E (TU2) (Fig. 1b). The difference in average soil water reserves on April 1 compared to the control makes it possible to rank the treatments from the worst to the best in terms of soil water reserves:

A(TG1) < F(TS2) < D(TG2) < B(TU1) < C(TS1) < I(TD2) < H(TD1) < E(TU2)

The number of days of limited access to soil water directly indicates the impact of water conditions on the possibilities of its uptake by stands. This indicator showed that the threat of soil drought in the thinning experiment occurred in 2015, 2016, and 2019, with only 2019 affecting all treatments of the experiment (Table 6). Compared to the control plot, plots A(TG1) and F(TS2) had more days with limited soil water (Fig. 1c). In the other treatments, the number of days with drought risk was lower than in the control plot. The difference in the number of days with limited soil water availability compared to the control allows the treatments to be ranked from most to least drought-prone:

A(TG1) < F(TS2) < D(TG2) < B(TU1) < C(TS1) < I(TD2) < H(TD1) < E(TU2)

Table 5.
Soil water storage at the beginning of the growing season

Year	Experiment variant / Type of thinning									
	A/TG1	B/TU1	C/TS1	D/TG2	E/TU2	F/TS2	G/K	H/TD1	I/TD2	Average
2011	198.4	201.2	201.4	201.0	202.5	199.8	199.9	201.7	201.4	200.8
2012	189.3	206.8	208.1	205.9	209.8	198.2	198.7	209.5	208.4	203.8
2013	200.0	209.8	209.8	209.8	209.8	209.8	209.8	209.8	209.8	208.7
2014	156.8	185.4	187.1	184.0	199.1	171.6	172.9	189.5	187.9	181.6
2015	209.8	209.8	209.8	209.8	209.8	209.8	209.8	209.8	209.8	209.8
2016	172.5	185.8	187.0	183.9	199.9	179.4	178.7	189.1	188.1	184.9
2017	161.7	181.1	185.1	176.9	205.2	167.0	166.0	191.1	187.5	180.2
2018	207.2	208.1	208.2	208.1	208.6	207.6	207.7	208.3	208.2	208.0
2019	115.7	162.1	164.8	159.5	188.3	135.0	138.2	169.1	166.8	155.5
2020	120.6	131.2	132.6	130.7	139.0	126.9	126.5	133.9	132.2	130.4
Average	173.2	188.1	189.4	187.0	197.2	180.5	180.8	191.2	190.0	186.4

Table 6.
Number of days with limited water availability for plants

Year	Experiment variant / Type of thinning									
	A/TG1	B/TU1	C/TS1	D/TG2	E/TU2	F/TS2	G/K	H/TD1	I/TD2	Average
2011	0	0	0	0	0	0	0	0	0	0.0
2012	0	0	0	0	0	0	0	0	0	0.0
2013	0	0	0	0	0	0	0	0	0	0.0
2014	0	0	0	0	0	0	0	0	0	0.0
2015	18	6	5	6	0	14	13	4	5	7.9
2016	40	0	0	0	0	22	21	0	0	9.2
2017	0	0	0	0	0	0	0	0	0	0.0
2018	6	0	0	0	0	0	0	0	0	0.7
2019	86	55	54	58	25	76	75	51	52	59.1
2020	0	0	0	0	0	0	0	0	0	0.0
Average	150	61	59	64	25	112	109	55	57	76.9

Discussion

Thinning is carried out to improve growing conditions in the stand by reducing competition between trees for access to nutrients, water, and light, and increasing the space occupied by individual trees (Martin-Benito *et al.*, 2010). Reducing the number of trees also affects tree photosynthetic activity (Gershenson *et al.*, 2009; Högberg, 2010), root activity, and labile organic carbon input (Kuzyakov, 2002; Zhu and Cheng, 2011). This thinning leads to stronger tree growth and better growth performance (Valinger *et al.*, 2000; Pukkala *et al.*, 2002; Mäkinen and Isomäki, 2004). In addition to the effects on tree growth, thinning also has a strong impact on the forest ecosystem. It leads to an increase in topsoil temperature and accelerates nitrogen mineralization (Thibodeau *et al.*, 2000), increases soil moisture (Davidson *et al.*, 2006), and increases tree resistance to insect attack (Coyea and Margolis, 1994).

Thinning results in a reduction in the number of trees and canopy density. Reducing foliage and increasing the proportion of gaps between crowns in a pine stand results in a reduction in rainfall interception of about 10% (Boczoń *et al.*, 2016). A similar effect was observed by Knoche (2005) who showed that in a ponderosa pine stand, a 40% reduction in stand density led to a reduction in rainfall interception from 38% to 31%. In a study by Chroust (1994), it was shown that a 25% reduction in basal area of a ponderosa pine stand reduced rainfall interception by 11.8% (from 24.6% to 12.8%). with the thinning effect lasting for 10 years. On the other hand, in a study by Slodicak *et al.* (2011), a 31% reduction in basal area resulted in only a 2-6% decrease in rainfall interception, and this effect lasted only 6 years.

Many researchers indicate that increased rainfall reaching the soil may be one of the main factors in increasing available soil water resources after thinning (Zahner and Whitmore, 1960; Cregg *et al.*, 1990; Stogsdill *et al.*, 1992; Breda *et al.*, 1995; Baumler and Zech, 1997). They also indicate that reduced evapotranspiration or transpiration is the second factor leading to an increase in soil water resources. The effect of thinning on transpiration has been studied by many authors, but the results show varying effects of the treatment. Breda *et al.* (1995) found a relationship between reduced transpiration in the stand and reduced basal area in *Quercus petraea* (Matt.) Liebl. stands. A similar result was found by Morikawa *et al.* (1986) in a stand of *Chamaecyparis obtusa* (Siebold & Zucc.) Endl. However, a study by Black *et al.* (1980) on transpiration of *Pseudotsuga menziesii* (Mirb.) Franco stands showed little or no effect of thinning on stand transpiration. A similar result was obtained for a *Pinus taeda* L. stand (Stogsdill *et al.*, 1992). In a study in a *Pinus sylvestris* L. stand, Vesala *et al.* (2005) also found no effect of thinning on total stand transpiration. In a study in a pine stand (Boczoń *et al.*, 2016) tree transpiration and ecosystem evapotranspiration indicate that these processes increased after thinning. Pine transpiration increased by 45%, while current evapotranspiration increased by 47%. More light reaches the crowns after thinning (Whitehead *et al.*, 1984) and the creation of spaces between crowns promotes better water vapour exchange and water vapour removal above the crowns. Allowing more light into the crowns is one of the reasons for thinning, because it accelerates tree growth by creating better conditions for photosynthesis. At the same time, it creates better conditions for tree transpiration.

The duration of the canopy loosening effect depends on the rate of crown growth. Crown growth filling the space created is also observed in pines (Baldwin *et al.*, 2000; Lockow, 2003). However, crown growth in older stands is less than in younger stands. Studies by Juodvalkis *et al.* (2005) have shown that when young stands are thinned (in pines these are 10-20-year-old stands) before commercial thinning, a more significant increase in crown volume growth can be achieved. In older age classes, crown growth does not exceed 10%. Sohn *et al.* (2016) suggest that shorter thinning is better suited to improve pine response to drought throughout the production cycle due to the observed decrease in regeneration with time after treatment.

Whitehead *et al.* (1984) believe that thinning reduces stand vulnerability to drought by reducing stand shielding and increasing soil water reserves. Similar conclusions were reached by Aussenac and Granier (1988) and Gracia *et al.* (1999). Positive effects of thinning on drought stress were found in a study of a 32-year-old black pine stand in Spain (Martin-Benito *et al.*, 2010) and a 22-year-old spruce stand in the Belgian Ardennes (Misson *et al.*, 2003). A relatively small change in the length of time that water is available to plants may be important for a stand to survive rainless periods. For example, Lagergren and Lindroth (2002) showed that a decrease in soil water availability greatly reduces transpiration in pine stands, so even a small increase in soil water content greatly affects the transpiration capacity of a stand.

The modelling studies and the three indices used to characterize soil water conditions showed large differences in response to the type of thinning of pine stands. The best effect was obtained with moderate thinning, although the results were clearer with lower thinning. Group thinning had the weakest effect on soil water balance and drought threat because too many trees were left competing for water. Strong thinning should also be considered less favourable than moderate thinning, which could be related to more intensive understory development under conditions of a permanently interrupted upper canopy.

Studies under climatic conditions similar to those in Poland – in the eastern part of the Czech Republic – have shown that intensive thinning (removal of 47% of trees and 31% of basal area) had a positive effect on the water balance of a young pine stand (Slodicak *et al.*, 2011). The positive effect was significant for four years after the first treatment. After the biomass of the stand increased, the positive effect of thinning disappeared. Studies in *Pinus sylvestris* and *Pinus nigra* Arn. stands have also shown that intensive thinning (removal of 60% of the cross-sectional area) is a promising way to adapt drought-sensitive Mediterranean pine forests to potential climate change threats (Navarro-Cerrillo *et al.*, 2019). The positive effect of reduced stand density on soil moisture was observed by Belmonte *et al.* (2022) in spruce stands, although they point to the implementation of moderate thinning, which should provide improved water conditions without negatively affecting biomass production.

Conclusions

- Thinning a mid-seral pine stand has a positive effect on stand water balance by reducing inter-individual competition for water resources.
- On the fresh conifer forest site, the most favourable conditions are created by moderate selective thinning, as well as low thinning that does not permanently disrupt the upper canopy of the trees.
- Strong thinning, *i.e.*, removing a large number of trees, which leads to intensive development of the understory, and weak thinning, which does not sufficiently reduce competition between trees, are less favourable compared to moderate thinning.

Authors' contributions

A.B. – concept development, manuscript planning, data collection, model research, literature review, analysis and interpretation, final text editing; T.Z. – data collection, literature review, analysis and interpretation.

Conflicts of interest

The authors declare no conflicts of interest regarding the publication of this paper.

Acknowledgments

The study was elaborated within the framework of the research project no 260222 financed from the Forest Research Institute's Research Fund.

References

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., Mcdowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H., 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. *Forest Ecology and Management*, 259: 660-684. DOI:10.1016/j.foreco.2009.09.001.

Aussenac, G., Granier, A., 1988. Effects of thinning on water stress and growth in Douglas-fir. *Canadian Journal of Forest Research*, 18: 100-105. DOI: https://doi.org/10.1139/x88-015.

Baldwin, V.C. Jr, Peterson, K.D., Clark, A., Ferguson, R.B., Strub, M.R., Bower, D.R., 2000. The effects of spacing and thinning on stand and tree characteristics of 38-year-old loblolly pine. *Forest Ecology and Management*, 137: 91-102. https://doi.org/10.1016/S0378-1127(99)00340-0.

Baumler, R., Zech, W., 1997. Atmospheric deposition and impact of forest thinning on the throughfall of mountain forest ecosystems in the Bavarian Alps. *Forest Ecology and Management*, 95: 243-251. DOI: https://doi.org/10.1016/S0378-1127(97)00039-X.

Belmonte, A., Ts. Sankey, T., Biederman, J., Bradford, J.B., Kolb, T., 2022. Soil moisture response to seasonal drought conditions and post-thinning forest structure. *Ecohydrology*, 15 (5): e2406. DOI: https://doi.org/10.1002/eco.240618.

Black, T.A., Tan, C.S., Nnyamah, J.U., 1980. Transpiration rate of Douglas fir trees in thinned and unthinned stands. *Canadian Journal of Soil Science*, 60: 625-631. DOI: https://doi.org/10.4141/cjss80-071.

Blunden, J., Arndt, D., Baringer, M. (eds.), 2011. State of the Climate in 2010. *Bulletin of the American Meteorological Society*, 92 (6): S1-S266. https://doi.org/10.1175/1520-0477-92.6.S1.

Boczoń, A., Dudzińska, M., Kowalska A., 2016. Effect of thinning on evaporation of Scots pine forest. *Applied Ecology And Environmental Research*, 14 (2): 367-379. DOI: http://dx.doi.org/10.15666/aeer/1402_367379.

Braun, S., de Witte, L.C., Hopf, S.E., 2020. Auswirkungen des Trockensommers 2018 auf Flächen der Interkantonalen Walddauerbeobachtung. *Schweizerische Zeitschrift für Forstwesen*, 171: 270-280. DOI: https://doi.org/10.3188/szf.2020.0270.

Breda, 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: 295-306. DOI: https://doi.org/10.1093/treephys/15.5.295.

Briffa, K.R., van der Schrier, G., Jones, P.D., 2009. Wet and dry summers in Europe since 1750: evidence of increasing drought. *International Journal of Climatology*, 29: 1894-1905. DOI: https://doi.org/10.1002/joc.1836.

Büntgen, U., Urban, O., Krusic, P.J. *et al*., 2021. Recent European drought extremes beyond Common Era background variability. *Nature Geoscience*, 14: 190-196. DOI: https://doi.org/10.1038/s41561-021-00698-0.

Burke, E.J., Brown, S.J., Christidis, N., 2006. Modeling the recent evolution of global drought and projections for the twenty-first century with the Hadley Centre climate model. *Journal of Hydrometeorology*, 7 (5): 1113-1125. DOI: https://doi.org/10.1175/JHM544.1.

Chroust, L., 1994. Effect of stand density and thinning on water interception in Scots pine stands. *Lesnictvi-Forestry*, 40: 409-416.

Coyea, M.R., Margolis, H.A., 1994. The historical reconstruction of growth efficiency and its relationship to tree mortality in balsam fir ecosystems affected by spruce budworm. *Canadian Journal of Forest Research*, 24 (11): 2208--2221. DOI: https://doi.org/10.1139/x94-284.

Davidson, E.A., Janssens, I.A., Luo, Y., 2006. On the variability of respiration in terrestrial ecosystems: moving beyond Q10. *Global Change Biology* 12 (2): 154-164. DOI: https://doi.org/10.1111/j.1365-2486.2005.01065.x.

Degirmendžić, J., Kożuchowski, K., Żmudzka, E., 2004. Changes of air temperature and precipitation in Poland in the period 1951-2000 and their relationship to atmospheric circulation. *International Journal of Climatology*, 24: 291-310. DOI: https://doi.org/10.1002/joc.1010.

Dubrovsky, M., Svoboda, M.D., Trnka, M., Hayes, M.J., Wilhite, D.A., Zalud, Z., Hlavinka, P., 2009. Application of relative drought indices in assessing climate change impacts on drought conditions in Czechia. *Theoretical and Applied Climatology*, 96: 155-171. DOI: https://doi.org/10.1007/s00704-008-0020-x.

Gershenson, A., Bader, N.E., Cheng, W., 2009. Effects of substrate availability on the temperature sensitivity of soil organic matter decomposition. *Global Change Biology* 15 (1): 176-183. DOI: https://doi.org/10.1111/j.1365-2486.2008.01827.x.

Gracia, C., Sabate, S., Martinez, J.M., Albeza, E., 1999. Functional responses to thinning. In: F. Rodá, J. Retana, C. Gracia, J. Bellot, eds. *Ecology of Mediterranean Evergreen Oak Forests*. Heidelberg: Springer-Verlag, pp. 329-338.

Högberg, P., 2010. Is tree root respiration more sensitive than heterotrophic respiration to changes in soil temperature? *New Phytologist*, 188 (1): 9-10. DOI: https://doi.org/10.1111/j.1469-8137.2010.03366.x.

Juodvalkis A., Kairiukstis L., Vasiliauskas R., 2005. Effects of thinning on growth of six tree species in north-temperate forests of Lithuania. *European Journal of Forest Research*, 124: 187-192. DOI: https://doi.org/10.1007/s10342-005-0070-x.

Knoche, D., 2005. Effects of stand conversion by thinning and underplanting on water and element fluxes of a pine ecosystem (*P. sylvestris* L.) on lignite mine spoil. *Forest Ecology and Management*, 212: 214-220. DOI: https://doi.org/10.1016/j.foreco.2005.03.038.

Komatsu, H., Shinohara, Y., Kume, T., Otsuki, K., 2008. Relationship between annual rainfall and interception ratio for forests across Japan. *Journal of Hydrology*, 256: 1189-1197. DOI: https://doi.org/10.1016/j.foreco.2008.06.036.

Kuzyakov, Y., 2002. Separating microbial respiration of exudates from root respiration in non-sterile soils: a comparison of four methods. *Soil Biology and Biochemistry*, 34 (11): 1621-1631. DOI: https://doi.org/10.1016/S0038-0717(02)00146-3.

Lagergren, F., Lindroth, A., 2002. Transpiration response to soil moisture in Pine and Spruce trees in Sweden. *Agricultural and Forest Meteorology*, 112: 67-85. DOI: https://doi.org/10.1016/S0168-1923(02)00060-6.

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolström, M., Lexer, M.J., Marchetti, M., 2010. Climate change impacts, adaptive capacity and vulnerability of European forest ecosystems. *Forest Ecology and Management*, 259: 698-709. DOI: https://doi.org/10.1016/j.foreco.2009.09.023.

Lockow, K.W., 2003. Wpływ trzebieży na dynamikę rozwoju drzewostanów sosnowych. (The effect of thinning regimes on the dynamics of Scots pine stand development) (in Polish). *Sylwan*, 9: 3-9. DOI: https://doi.org/10.26202/sylwan.2003203.

Mäkinen, H., Isomäki, A., 2004. Thinning intensity and growth of Scots pine stands in Finland. *Forest Ecology and Management*, 201: 311-325. DOI: https://doi.org/10.1016/j.foreco.2004.07.016.

Martin-Benito, D., Del Rio, M., Heinrich, I., Helle, G., Canellas, I., 2010. Response of climate-growth relationships and water use efficiency to thinning in a *Pinus nigra* afforestation. *Forest Ecology and Management*, 259: 967-975. DOI: https://doi.org/10.1016/j.foreco.2009.12.001.

Misson, L., Vincke, C., Devillez, F., 2003. Frequency responses of radial growth series after different thinning intensities in Norway spruce (*Picea abies* (L.) Karst.) stands. *Forest Ecology and Management*, 177: 51-63. DOI: https://doi.org/10.1016/S0378-1127(02)00324-9.

Morikawa, Y., Hattori, S., Kiyono, Y., 1986. Transpiration of a 31-year-old *Chamaecyparis obtusa* Endl. stand before and after thinning. *Tree Physiology*, 2: 105-114. DOI: https://doi.org/10.1093/treephys/2.1-2-3.105.

Navarro-Cerrillo, R.M., Sánchez-Salguero, R., Rodriguez, C., Lazo, J.D., Moreno-Rojas, J.M., Palacios--Rodriguez, G., Camarero, J.J., 2019. Is thinning an alternative when trees could die in response to drought? The case of planted *Pinus nigra* and *P. sylvestris* stands in southern Spain. *Forest Ecology and Management*, 433: 313-324. DOI: https://doi.org/10.1016/j.foreco.2018.11.006.

Pukkala, T., Miina, J., Palahi, M., 2002. Thinning response and thinning bias in a young Scots pine stand. *Silva Fennica*, 36: 827-840. DOI: https://doi.org/10.14214/sf.524.

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., Rigling, A., Rose, L., Ruehr, N.K., Schumann, K., Weiser, F., Werner, C., Wohlgemuth, T., Zang, C.S., 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. DOI: https://doi.org/10.1016/j.baae.2020.04.003.

Slodicak, M., Novak, J., Dusek, D., 2011. Canopy reduction as a possible measure for adaptation of young Scots pine stand to insufficient precipitation in Central Europe. *Forest Ecology and Management*, 262: 1913-1918. DOI: https://doi.org/10.1016/j.foreco.2011.02.016.

Sohn, J.A., Hatig, F., Kohler, M., Huss, J., Bauhus, J., 2016. Heavy and frequent thinning promotes drought adaptation in *Pinus sylvestris* forests. *Ecological Applications*, 26: 2190-2205. DOI: https://doi.org/10.1002/eap.1373.

Stogsdill, W.R., Wittwer, R.F., Hennessey, T.C., Dougherty, P.M., 1992. Water-use in thinned loblolly pine plantations. *Forest Ecology and Management*, 50: 233-245. DOI: https://doi.org/10.1016/0378-1127(92)90338-A.

Thibodeau, L., Raymond, P., Camire, C., Munson, A.D., 2000. Impact of precommercial thinning in balsam fir stands on soil nitrogen dynamics, microbial biomass, decomposition, and foliar nutrition. *Canadian Journal of Forest Research*, 30: 229-238. DOI: https://doi.org/10.1139/x99-202.

Valinger, E., Elfving, B., Mörling, T., 2000. Twelve-year growth response of Scots pine to thinning and nitrogen fertilisation. *Forest Ecology and Management*, 134: 45-53. DOI: https://doi.org/10.1016/S0378-1127(99)00244-3.

Vesala, T., Suni, T., Rannik, U., Keronen, P., Markkanen, T., Sevanto, S., Gronholm, T., Smolander, S., Kulmala, M., Ilvesniemi, H., Ojansuu, R., Uotila, A., Levula, J., Makela, A., Pumpanen, J., Kolari, P., Kulmala, L., Altimir, N., Berninger, F., Nikinmaa, E., Hari, P., 2005. Effect of thinning on surface fluxes in a boreal forest. *Global Biogeochemical Cycles*, 19: GB2001. DOI: https://doi.org/10.1029/2004GB002316.

Wang, Q., Wu, J., Lei, T., He, B., Wu, Z., Liu, M., Mo, X., Geng, G., Li, X., Zhou, H., Liu, D., 2014. Temporal-spatial characteristics of severe drought events and their impact on agriculture on a global scale. *Quaternary International*, 349: 10-21. DOI: https://doi.org/10.1016/j.quaint.2014.06.021.

Whitehead, D., Jarvis, P.G., Waring, R.H., 1984. Stomatal conductance, transpiration, and resistance to water uptake in a *Pinus sylvestris* spacing experiment. *Canadian Journal of Forest Research*, 14: 692-700. DOI: https://doi.org/10.1139/x84-124.

Zhu, B., Cheng, W., 2011. Rhizosphere priming effect increases the temperature sensitivity of soil organic matter decomposition. *Global Change Biology*, 17 (6): 2172-2183. DOI: https://doi.org/10.1111/j.1365-2486.2010.02354.x.

STRESZCZENIE

Wpływ różnych metod trzebieży na zasoby wodne gleby i ryzyko suszy glebowej w drzewostanach sosnowych

Zmiany klimatu powodują, ze susze stają się coraz większym zagrożeniem dla drzewostanów. Przewiduje się, że skutkiem zmian klimatu będzie w środkowej Europie cieplejsza i bardziej bezdeszczowa pogoda w okresie wegetacji (Degirmendžić i in. 2004; Briffa i in. 2009; Dubrovsky i in. 2009; Lindner i in. 2010). Stres suszy jest postrzegany jako ważne zagrożenie dla witalności i wzrostu drzew, mogący ostatecznie prowadzić do ich zamierania (Allen i in. 2010). Susze w latach 2018-2019 spowodowały zniszczenie lub obumarcie drzewostanów iglastych i liściastych na dużych obszarach Europy (Braun i in. 2020; Schuldt i in. 2020). Wielu badaczy wskazuje, że trzebież może być jednym z głównych czynników wpływających na zwiększenie zasobów dostępnej wody glebowej (Zahner i Whitmore 1960; Cregg i in. 1990; Stogsdill i in. 1992; Breda i in. 1995; Baumler i Zech 1997).

Celem badań było określenie wpływu sposobu wykonania trzebieży na zasoby wody glebowej oraz liczbę dni z deficytem wody glebowej jako wskaźnika ryzyka stresu suszy.

Badania przeprowadzono na powierzchni doświadczalnej w Nadleśnictwie Kozienice, na której w 1965 r. posadzono sadzonki sosny zwyczajnej na siedlisku boru świeżego, I bonitacji, na glebie rdzawej właściwej. Doświadczenie założono, obejmując następujące warianty trzebieży i uwzględniając więźbę sadzenia:

– wariant G (więźba sadzenia prostokątna 1,2×0,8 m) powierzchnia kontrolna (K),
– wariant A (więźba sadzenia kwadratowa 0,8 m) i D (więźba sadzenia trójkątna 1,0 m), obecnie oznaczane jako trzebież grupowa (odpowiednio TG1 i TG2),
– wariant B (więźba sadzenia kwadratowa 1,0 m) i E (więźba sadzenia trójkątna 1,2 m), obecnie oznaczane jako trzebież umiarkowana (odpowiednio TU1 i TU2),
– wariant C (więźba sadzenia kwadratowa 1,2 m) i F (więźba sadzenia prostokątna 1,2×0,55 m), obecnie oznaczane jako trzebież silna (TS1 i TS2),
– wariant H (więźba sadzenia prostokątna 2,30×0,30 m) i I (więźba sadzenia kwadratowa 1,4 m), obecnie umiarkowana trzebież dolna (TUD).

Biometryczna charakterystyka drzewostanów w poszczególnych wariantach doświadczenia w 2020 r. została przedstawiona w tabeli 1.

Bilans wodny na powierzchniach trzebieżowych określono na podstawie modelowania zmian dobowego zapasu wody glebowej (SWS) w profilu do 100 cm głębokości, obliczanego z różnicy przychodu wody z opadów oraz odpływu wody w procesie ewapotranspiracji, z uwzględnieniem właściwości retencyjnych gleby. Dane wejściowe do modelu różnicujące drzewostany w wariantach doświadczenia zestawiono w tabeli 2, a charakterystykę danych meteorologicznych lat poddanych badaniom modelowym w tabeli 3. Do określenia zróżnicowania zasobów wodnych w poszczególnych wariantach wykonanej trzebieży zastosowano 3 wskaźniki: 1 – średni roczny zapas wody glebowej, 2 – zapas wody glebowej na początku okresu wegetacyjnego (przyjęto 1 kwietnia), 3 – liczba dni z ograniczoną wodą dostępną dla roślin.

W stosunku do wariantu kontrolnego (G) mniejsze średnioroczne zasoby wody glebowej odnotowano na powierzchni A z trzebieżą grupową (TG1) oraz w wariancie F z trzebieżą silną (TS2), ale w tym przypadku różnica była bardzo nieznaczna (ryc. 1a, tab. 4). Pozostałe warianty trzebieży charakteryzowały wyższe zasoby wodne od kontroli.

Zapas wody glebowej na początku półrocza letniego pokazuje, że warianty doświadczenia A (TG1) i F (TS2) miały 1 kwietnia niższe średnie zasoby wody glebowej niż kontrola. W pozostałych wariantach były wyższe, a najwyższe stwierdzono w wariancie E (TU2) (ryc. 1b, tab. 5).

Na powierzchniach A(TG1) i F(TS2) odnotowano w porównaniu z powierzchnią kontrolną większą liczbę dni ograniczonego dostępu wody glebowej (ryc. 1c, tab. 6). W pozostałych wariantach liczba dni zagrożenia suszą była mniejsza niż na powierzchni kontrolnej.

Przeprowadzone badania modelowe pokazały duże zróżnicowanie w reakcji na rodzaj wykonanej trzebieży w drzewostanach sosnowych. Najlepszy efekt uzyskano przy trzebieży umiarkowanej, z tym że bardziej jednoznaczne wyniki odnotowano w przypadku trzebieży umiarkowanej dolnej. Najsłabszy efekt dla warunków wodnych gleb i zagrożenia suszą dawała trzebież grupowa, ze względu na pozostawienie zbyt dużej liczby drzew konkurujących o wodę. Również trzebież silną należy uznać za mniej korzystną niż trzebieże umiarkowane, co może być spowodowane intensywniejszym rozwojem runa leśnego w warunkach trwale przerwanego okapu drzewostanu.