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Rozprawa doktorska

Czynniki środowiskowe kształtujące przyrost roczny sosny zwyczajnej (*Pinus sylvestris* L.) na wybranych stanowiskach w Polsce północnej

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Artykuł nr 1: Waszak, N.; Robertson, I.; Puchałka, R.; Przybylak, R.; Pospieszyńska, A.; Koprowski, M. Investigating the Climate-Growth Response of Scots Pine (*Pinus sylvestris* L.) in Northern Poland. Atmosphere 2021,12,1690.
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Spis treści

STRESZCZENIE

Zmiany klimatyczne obserwowane w ostatnich dekadach manifestują się globalnym wzrostem temperatur i zmianą reżimu opadów, zarówno w zakresie przestrzennym, jak i ich intensywności oraz wzrostem występowania zdarzeń ekstremalnych, co ma istotny wpływ na ekosystemy leśne. Badania zależności zachodzących między wzrostem drzew, a zmiennymi klimatycznymi i wpływem antropogenicznym na drzewostany mogą być klucze w przewidywaniu ich przyszłych reakcji. Analiza wzorców wzrostu sosny zwyczajnej (*Pinus sylvestris* L.), jako dominującego gatunku lasotwórczego w północnej Polsce, stanowi podstawę do lepszego zrozumienia jej możliwych reakcji na prognozowane zmiany klimatu.

Nadrzędnym celem pracy doktorskiej było zbadanie wpływu obserwowanych zmian klimatu oraz działalności człowieka na przyrosty roczne drzew gatunku sosny zwyczajnej, zarówno na poziomie makroskopowym (analiza słojów rocznych drzew), jak i mikroskopowym (analiza parametrów komórek w oparciu o preparaty mikroskopowe), wykorzystując dane klimatyczne o rozdzielczości dobowej i miesięcznej, z 23 stanowisk leśnych znajdujących się w północnej Polsce. Wyniki przedstawiono w postaci trzech spójnych tematycznie prac naukowych, na które złożyły się dwa artykuły naukowe opublikowane w międzynarodowych czasopismach o wysokim wskaźniku wpływu oraz manuskryptu naukowego złożonego do recenzji w czasopiśmie naukowym.

Pierwsze badanie, przeprowadzone na drzewostanie rosnącym w okolicach Torunia, dotyczyło analizy zależności między szerokością słojów rocznych drzew a zmiennymi klimatycznymi. Wyniki wykazały, że zarówno opady atmosferyczne, jak i temperatura mają istotny wpływ na szerokość słojów drzew, szczególnie w miesiącach wiosennych (marzec, kwiecień) oraz w okresie letnim. Opady okazały się mieć największy wpływ na przyrosty w czerwcu, podczas gdy temperatury istotnie wpływały na wzrost drzew w lutym i marcu. Dane dobowe okazały się być bardziej precyzyjnym wskaźnikiem ekstremalnych zjawisk pogodowych, w porównaniu z danymi miesięcznymi, dzięki czemu dokładniej odzwierciedliły wpływ klimatu na formowanie się szerokości słojów rocznych. Na podstawie badań wyodrębniono również lata charakteryzujące się wyjątkowo wąskimi przyrostami rocznymi, spowodowanymi ekstremalnymi warunkami klimatycznymi. Drugie badanie dotyczyło analizy wpływu nawożenia dna lasu ściekami poprodukcyjnymi na strukturę anatomiczną przyrostów rocznych drzew, rosnących w pobliżu fabryki skrobi ziemniaczanej w Iławie. Celem badań była odpowiedź na pytanie, jak różna intensywność nawożenia wpływa na parametry komórkowe

sosny. W latach cechujących się niskim stężeniem biogenów w mieszaninie ścieków, zaobserwowano pozytywny wpływ na szerokość pierścieni rocznych i średnicę komórek w drewnie, podczas gdy w okresie o wysokim stężeniu biogenów zaobserwowano zmniejszenie grubość ścian komórkowych oraz szerokości słojów. Zbyt duże stężenie substancji odżywczych, szczególnie potasu, przyczyniło się do zmniejszenia grubości ściany komórkowej, światła komórki, a także szerokości całego przyrostu rocznego, wskazując na możliwość wystąpienia suszy fizjologicznej i ograniczenie zdolności drzew do pobierania wody, pomimo jej wystarczającej dostępności w glebie. Trzecie badanie dotyczyło analizy parametrów klimatycznych, określając ich wpływ na wzrost sosny zwyczajnej w różnych częściach północnej Polski. Wschodnie regiony kraju, charakteryzujące się cechami klimatu kontynentalnego, wykazywały negatywne reakcję na wysokie temperatury w okresie letnim, jednocześnie opady czerwca miały pozytywny wpływ na wzrost drzew, co sugeruje, że susze letnie mogą ograniczać ich wzrost, jednakże większe sumy opadów latem są w stanie łagodzić skutki susz. W zachodniej Polsce, będącej pod wpływem przejściowego klimatu oceanicznego, sosny cechowały się szerszymi przyrostami rocznymi w wyniku wyższych temperatur w zimie oraz wczesną wiosną, co wskazuje na pozytywny wpływ cieplejszych zim na przyspieszenie okresu wegetacyjnego i związaną z tym szybszą aktywację podziałów kambialnych.

Badania zaprezentowane w nieniejszej pracy i opublikowane lub wysłane do recenzji podkreślają wieloaspektową dynamikę wzrostu drzew, która zależy od czynników zarówno naturalnych, jak i antropogenicznych. Analizy te dostarczają cennych informacji o wpływie zmian klimatycznych oraz działalności człowieka na zdrowie i wzrost lasów, wskazując na potrzebę dalszych badań w kontekście ich adaptacji do zmieniających się warunków środowiskowych.

ABSTRACT

The climatic changes observed in recent decades are manifested by a global increase in temperatures, a shift in precipitation regimes, both spatially and in their intensity, and an increase in extreme events with significant impacts on forest ecosystems. Investigating the relationships between tree growth and climatic variables and anthropogenic impacts on forest stands can be key in predicting their responses. Analysis of the growth patterns of Scots pine (*Pinus sylvestris* L.), the dominant forest-forming species in northern Poland, provides a basis for better understanding its possible responses to projected climate change.

The overarching aim of the dissertation was to investigate the effects of observed climate change and human activities on the annual growth of Scots pine trees, both at the macroscopic level (analysis of annual tree rings) and at the microscopic level (analysis of cell parameters based on microscopic slides), using daily and monthly resolution climate data from 23 forest sites located in northern Poland. The results were presented in three thematically coherent scientific papers: two scientific articles published in international high-impact journals and a scientific manuscript submitted for review in a scientific journal.

The first study, conducted on trees growing near Toruń, analysed the relationship between the width of annual tree rings and climatic variables. The results showed that both precipitation and temperature significantly affect the width of tree rings, especially in the spring months (March, April) and during the summer. Precipitation appeared to have the most significant effect on growth in June, while temperatures significantly affected tree growth in February and March. Daily data proved to be a more precise indicator of extreme weather events than monthly data. Thus, it more accurately reflected the influence of climate on the formation of annual tree ring widths. The study also identified years characterised by exceptionally narrow annual increments due to extreme climatic conditions. The second study analysed the effect of fertilisation of the forest floor with post-production wastewater on the anatomical structure of annual increments of trees growing near the potato starch factory in Ilawa. The study aimed to answer how different fertilisation intensities affect the cellular parameters of pine trees. In years characterised by a low concentration of nutrients in the effluent mixture, a positive effect on the width of annual rings and the diameter of cells in the wood was observed, whereas, in the period with a high concentration of nutrients, a reduction in the thickness of cell walls and the width of rings was observed. Excessive nutrient concentrations, especially of potassium, contributed to a decrease in cell wall thickness, cell lumen, and the width of the entire annual increment, indicating the possibility of physiological drought and a reduction in the trees' ability

to take up water despite their sufficient availability in the soil. The third study was concerned with analysing climatic parameters and determining their influence on Scots pine growth in different parts of northern Poland. The eastern regions of the country, characterised by continental climate features, showed a negative response to high summer temperatures, while at the same time, June precipitation had a positive effect on tree growth, suggesting that summer droughts may limit tree growth; however, higher summer precipitation totals are able to mitigate the impact of droughts. In western Poland, which is under the influence of a transitional oceanic climate, pines were characterised by wider annual increments as a result of higher temperatures in winter and early spring, indicating a positive effect of warmer winters on the acceleration of the growing season and the associated faster activation of cambial divisions.

The research presented in the present paper, published or sent for review, highlights the multifaceted dynamics of tree growth, which depends on both natural and anthropogenic factors. These analyses provide valuable information on the impact of climate change and human activities on forest health and growth, indicating the need for further research in the context of their adaptation to changing environmental conditions.

1. WSTĘP

Zmiany klimatu stanowią jedno z najistotniejszych wyzwań dla współczesnego zarządzania zasobami leśnymi, wpływając na wzrost, stan zdrowia i produktywność drzew. Sosna zwyczajna (*Pinus sylvestris* L.), jako jeden z najbardziej rozpowszechnionych gatunków w Europie, odgrywa kluczową rolę w badaniach dendroklimatologicznych, stanowiąc cenny materiał do analizy reakcji drzew na zmieniające się warunki środowiskowe [Bouriaud, Popa 2009; Opała 2015; Gričar 2019; Harvey i in. 2020]. Dzięki swojej szerokiej dystrybucji na półkuli północnej [Helama, Lindholm 2003; Matyas i in. 2004; Hökkä i in. 2012; Helama i in. 2014; Shestakova i in. 2017], sosna wykorzystywana jest do opracowywania długoterminowych chronologii pierścieni drzew, umożliwiających rekonstrukcję warunków klimatycznych. W Polsce, gdzie sosna zwyczajna jest dominującym gatunkiem leśnym [Biuro Urządzania Lasu i Geodezji Leśnej 2024], badania dendroklimatologiczne stanowią istotne narzędzie w rekonstrukcji klimatu, w tym w analizie wydarzeń ekstremalnych, takich jak susze czy zmiany temperatury powietrza i wpływie tych zdarzeń na przyrost drzew. Współczesne zmiany klimatyczne, przejawiające się w globalnym wzroście temperatury oraz modyfikacjach rozkładu opadów, mają istotny wpływ na dynamikę wzrostu drzew, szczególnie w regionach, w których występują warunki przejściowe między różnymi typami klimatu [Zunde i in. 2008; Metslaid i in. 2018; Harvey i in. 2020]. W Polsce, charakteryzującej się klimatem przejściowym, gdzie spotykają się cechy klimatu oceanicznego i kontynentalnego, drzewa mogą reagować odmiennie na zmiany temperatury i opadów w zależności od lokalizacji. Badania prowadzone w Skandynawii [Reich, Oleksyn 2008] wykazały, że ocieplenie klimatu sprzyja drzewom iglastym w regionach północnych, podczas gdy w rejonach południowych ma ono negatywny wpływ, co podkreśla regionalne różnice w reakcjach drzew na wzrost temperatury. Długotrwałe ocieplenie może wpłynąć na wydłużenie okresu wegetacyjnego, co teoretycznie mogłoby sprzyjać wzrostowi rocznemu, jednak częstsze i intensywniejsze susze letnie mogą negatywnie wpływać na rozwój roślinności, zwłaszcza w przypadku drzew iglastych [Graczyk, Kundzewicz 2016; Wertz, Wilczyński 2022]. Wzrost średnich rocznych temperatur i zmiany w rozkładzie opadów atmosferycznych, prowadzą do modyfikacji dotychczasowych wzorców klimatycznych, co z kolei oddziałuje na produkcję biomasy w ekosystemach leśnych. Wzrost temperatury oraz zmieniające się warunki wodne są kluczowe w analizie reakcji ekosystemów leśnych na zmiany środowiskowe [Lévesque i in. 2016; Messaoud, Reid 2020; Yuan i in. 2021; Ren i in. 2022; Wang i in. 2023]. W kontekście badań nad wzrostem drzew, dostępność wody jest jednym z głównych czynników, którego zmiany mogą być wynikiem zarówno procesów klimatycznych, jak i działalności antropogenicznej [Lévesque i in. 2016]. Przykładem niech będzie stosowanie nawozów mineralnych oraz wód poprodukcyjnych z przemysłu skrobiowego, zastosowanych w celu poprawy wzrostu biomasy leśnej oraz zagospodarowania odpadów [A. Ciepielowski i in. 1999; Koprowski i in. 2015; Chojnacka-Ożga i in. 2022]. Chociaż nawożenie może prowadzić do zwiększenia biomasy [Balster, Marshall 2000; Lindkvist i in. 2011; Hedwall i in. 2014], nadmierne wprowadzanie składników odżywczych, szczególnie w wodach odpadowych, może wpłynąć negatywnie na kondycję drzew, prowadząc do zaburzeń w ich wzroście i odporności na stres hydrologiczny [Peters 1972; Gumnicka 1999; Koprowski i in. 2015]. Pomimo licznych badań nad wpływem zmian klimatycznych na wzrost drzew, wciąż istnieje potrzeba pogłębionych analiz dotyczących złożonych interakcji zachodzących między czynnikami klimatycznymi, praktykami leśnymi oraz reakcjami drzewostanów na zmieniające się warunki środowiskowe. W Polsce, gdzie zmiany klimatyczne objawiają się wzrostem temperatury oraz modyfikacjami w rozkładzie opadów, szczególnie istotne staje się zrozumienie, jak sosna zwyczajna reaguje na te wahania w kontekście regionalnych różnic klimatycznych oraz długoterminowych trendów, które mogą mieć istotny wpływ na przyszłość polskich lasów.

Celem niniejszej pracy jest analiza dynamiki wzrostu drzew sosny zwyczajnej na różnych poziomach – zarówno na poziomie makroskalowym (wzrost roczny, szerokość słojów), jak i mikroskalowym (struktura anatomiczna przyrostów rocznych). W pracy dokonano szczegółowej analizy wpływu zmiennych klimatycznych, takich jak temperatura i opady, na przyrosty roczne drzew sosny zwyczajnej na przestrzeni ostatnich kilku dziesięcioleci, z uwzględnieniem regionalnych różnic klimatycznych północnej Polski. Ponadto, zbadano wpływ nawożenia na strukturę anatomiczną przyrostów rocznych, analizując reakcje drzew na zmiany w dostępności składników odżywczych, takich jak azot, fosfor i potas, wprowadzonych w formie odpadów poprodukcyjnych. Praca opiera się na trzech odrębnych artykułach badawczych, które analizują zarówno długoterminowe zmiany klimatyczne, jak i wpływ działań antropogenicznych na wzrost drzew. Wyniki badań mają na celu lepsze zrozumienie mechanizmów odpowiedzi sosny zwyczajnej na zmieniające się warunki środowiskowe, co może przyczynić się do poprawy praktyk leśnych i zarządzania zasobami leśnymi w obliczu postępujących zmian klimatycznych oraz rosnącej presji związanej z działalnością człowieka. Zastosowanie różnych skal czasowych (od dobowych po miesięczne dane klimatyczne) oraz technik mikroskalowych (analiza anatomiczna słojów) pozwala na uzyskanie precyzyjnych informacji na temat mechanizmów wzrostu sosen w odpowiedzi na zmiany warunków klimatycznych oraz wpływu nawożenia. Celem pracy jest nie tylko analiza tych zależności, ale także wyciągnięcie wniosków dotyczących przyszłych kierunków badań w zakresie ekologii i zarządzania lasami.

2. CEL BADAŃ

Głównym celem niniejszej rozprawy było rozpoznanie dynamiki wzrostu drzew gatunku sosny zwyczajnej na dwóch poziomach: analizy słojów przyrostów rocznych i struktury słojów na poziomie komórkowym. Reakcje przyrostowe drzew przeanalizowano w aspekcie czasowym na drzewostanach rosnących na 23 stanowiskach w północnej Polsce. Przyczyn określonych reakcji przyrostowych poszukiwano we wpływie zmiennych elementów klimatycznych (temperatury powietrza i opadów atmosferycznych) (artykuł nr 1 i 3) oraz znaczeniu nawożenia dna lasu industrialnymi odpadami poprodukcyjnymi (artykuł nr 2) prowadzącymi do wzrostu stężenia azotu, potasu i fosforu w glebie.

Cele szczegółowe dotyczyły odpowiedzi na następujące pytania:

Artykuł nr 1:

- Jak kształtuje się relacja przyrost-klimat w zależności od tego czy korzystamy z klimatycznych danych dobowych czy miesięcznych?
- Które dane, dobowe czy miesięczne, są bardziej odpowiednie do przeprowadzenia analiz klimatycznych i rekonstrukcji klimatu?

Artykuł nr 2:

- W jaki sposób drzewostan sosnowy z okolic Iławy zareagował, w latach 1984-2009, na zmianę reżimu dostarczanych składników odżywczych?
- Jak różne stężenia pierwiastków azotu (N), fosforu (P) i potasu (K) zawarte w ściekach poprodukcyjnych z fabryki skrobi ziemniaczanej wpłynęły na strukturę anatomiczną drewna sosny zwyczajnej?

Artykuł nr 3:

- Jak kształtują się reakcje przyrostu sosny zwyczajnej rosnącej w północnej Polsce na zmienne klimatyczne, w trzech równych przedziałach czasowych: 1951-1973, 1974-1996, 1997-2019?
- Czy reakcja drzew rosnących w strefie przejścia pomiędzy klimatem kontynentalnym a oceanicznym jest taka sama na całym obszarze czy zależy od wpływu stref klimatycznych?

3. MATERIAŁY I METODY

3.1. Teren badań

Badania prowadzone były w okolicach Torunia (Artykuł nr 1) i Iławy (Artykuł nr 2) oraz na 23 stanowiskach leśnych w Polsce północnej obejmujących pas terenu od okolic Szczecina na zachodzie do miejscowości Żytkiejmy oraz Siedlce na wschodzie (Artykuł nr 3). W analizowanych drzewostanach sosna zwyczajna była dominującym gatunkiem lasotwórczym.

Artykuł nr 1:

Teren badań położony jest w województwie kujawsko-pomorskim w północnej części miasta Torunia, o średniej wysokości 65 m n.p.m. i porośnięty jest świeżym lasem mieszanym zdominowanym przez sosnę zwyczajną (*Pinus sylvestris* L.) i dąb szypułkowy (*Quercus robur* L.). Jest to siedlisko umiarkowanie żyzne, raczej wilgotne, o niskim poziomie wód gruntowych i stosunkowo niskiej sumie opadów (średnia roczna suma opadów za lata 1961-2004 wyniosła 536 mm).

Artykuł nr 2:

Teren badań znajduje się w północnej części Polski, w Nadleśnictwie Iława, na Pojezierzu Brodnickim, kilka kilometrów na południe od miasta Iława, na terenie nieistniejącej już Leśnej Oczyszczalni Ścieków, prowadzącej swoją działalność w latach 1984-2012. Oczyszczalnia została zaprojektowana w celu odprowadzania ścieków z fabryki skrobi ziemniaczanej do gleby leśnej. Celem było rozprowadzenie ścieków w celu ich oczyszczenia i przyczynienia się do zwiększenia produktywności drzewostanu. Obiekt powstał na 216 ha lasu sosnowego rosnącego na glebach bielicowych i rdzawych, wykształconych na piaskach słabo gliniastych i luźnych o małej zdolności retencyjnej [Brandyk i in. 1999]. Do przeprowadzenia analiz wybrano dwa obszary na terenie oczyszczalni, bezpośrednio nawożony (stanowisko nr 1) oraz nienawożony (stanowisko nr 2), oddalone od siebie o 0,5 km oraz znajdujący poza oczyszczalnią teren kontrolny (stanowisko nr 3) położony w odległości 1,5 km. Gleba była tego samego typu w każdej z trzech lokalizacji. Średnia roczna temperatura powietrza i średnie roczne opady dla tego regionu wynoszą 7,6 $^{\circ}$C i 610 mm w okresie 1951-2020.

Artykuł nr 3:

Badania przeprowadzono w północnej Polsce na 23 stanowiskach, obejmujących dwie główne prowincje: Niż Środkowoeuropejski oraz Niż Wschodniobałtycko-Białoruski

[Kondracki 2002]. Niż Środkowoeuropejski, z wyraźnymi granicami północnymi i południowymi, charakteryzuje się mniej precyzyjnie określonymi granicami wschodnimi i zachodnimi. Południowo-zachodnia część Niziny Wschodniobałtycko-Białoruskiej znajduje się w granicach Polski i ma podobny układ rzeźby terenu do polskiej części Niżu Środkowoeuropejskiego, a płaska powierzchnia obydwu nizin ułatwia przemieszczanie się mas powietrza morskiego w głąb wschodnich rejonów kraju. W zachodniej części Niżu Środkowoeuropejskiego dominuje klimat oceaniczny, podczas gdy część wschodnia wykazuje cechy klimatu przejściowego między oceanicznym a kontynentalnym. Pierwotnie tereny te porastały głównie lasy liściaste i mieszane, które na obszarach piaszczystych ustąpiły miejsca borom sosnowym i wrzosowiskom. Obecnie, w skutek działalności człowieka, głównym gatunkiem lasotwórczym jest sosna zwyczajna.

3.2. Dane klimatyczne

Wykorzystane w analizie dane klimatyczne pochodzą ze stacji IMGW w Toruniu (53°04'N, 18°59'E) (Artykuł nr 1). W artykule nr 2 użyto danych klimatycznych (miesięczna suma opadów atmosferycznych oraz miesięczna średnia temperatura powietrza) ze stacji IMGW w Olsztynie (53°46'N, 20°25'E), oddalonej o 55 km od obszaru badań w pobliżu miasta Iława, ponieważ była to najbliższa dostępna stacja pomiarowa. W artykule nr 3, dobowe dane klimatyczne (średnia temperatura oraz suma opadów), które następnie uśredniono lub zsumowano do danych miesięcznych, pobrano z bazy danych klimatycznych E-OBS (wersja 28.0e, regularna siatka 0,1 stopnia) dla okresu 1950–2019 dla punktów położonych najbliżej każdego z 23 stanowisk badawczych [Cornes i in. 2018].

3.3 Materiał badawczy

Artykuł nr 1 i 3:

Materiał badawczy w postaci 100 wywiertów z 50 drzew zebrano po zakończeniu sezonu wegetacyjnego, późną jesienią i zimą 2019 roku (Artykuł nr 1), zaś 350 wywiertów ze 175 drzew, z 7 stanowisk w Polsce północnej (25 drzew na stanowisko), zebrano latem 2022 roku (Artykuł nr 3). W artykule nr 3 wykorzystano obydwa powyższe zbiory danych, łącznie 450 wywiertów z 225 drzew, jak również 15 chronologii zgromadzonych w Pracowni Dendrochronologicznej Uniwersytetu Mikołaja Kopernika. Wytypowane drzewa były zdrowe, z prostym pniem i regularną koroną. Wywierty zebrano z około 175-letnich sosen, z najstarszym słojem datowanym na 1847 rok (Artykuł nr 1) oraz około 100-letnich drzewostanów, z najstarszym słojem datowanym na 1833 rok (Artykuł nr 3). Z każdego drzewa pobrano dwie próby na wysokości pierśnicy (1,3 m nad ziemią) za pomocą świdra Presslera o średnicy 5 mm przy użyciu standardowych technik. Rdzenie zostały przygotowane do pomiarów przy użyciu standardowych procedur dendrochronologicznych. Wywierty wysuszono, ścięto ostrym nożem i zeskanowano z rozdzielczością 1200 DPI przy użyciu skanera: Epson Perfection V700 Photo. Do pomiaru szerokości słojów drzew z dokładnością do 0,01 mm użyto programów CooRecorder 9.3.1 i CDendro 9.3.1 (http://www.cybis.se; dostęp 10 grudnia 2021 r.; [Larsson, Larsson 2014]). Oprogramowanie COFECHA 6.06P [Grissino-Mayer 2001] zostało użyte do sprawdzenia wzajemnej korelacji między seriami, wykrycia brakujących słojów i możliwych błędów datowania.

Artykuł nr 2:

Według informacji przekazanych przez Nadleśnictwo Iława, drzewa były w podobnym wieku, około 105 lat w 2009 roku, kiedy to próby zostały pobrane. Drzewa nie wykazywały widocznych oznak choroby. Jednak na nawożonym stanowisku 1 gęstość drzew była niższa ze względu na samoistne przerzedzenie. Za pomocą standardowego świdra Presslera o średnicy 5 mm pobrano 120 rdzeni z sosen rosnących na trzech stanowiskach (40 rdzeni na stanowisko). Z każdego drzewa pobrano dwie próby, jedną od strony zachodniej i jedną od strony wschodniej, na wysokości pierśnicy (1,3 m nad ziemią). Rdzenie zostały przygotowane do pomiaru przy użyciu standardowych procedur dendrochronologicznych [Zielski, Krąpiec 2004], a przyrosty roczne drzew zostały przeanalizowane przez Koprowski i in. [2015].

3.3.1. Wybór drzew do ilościowej anatomii drewna (QWA)

Artykuł nr 2:

Do badań anatomicznych drewna wybrano łącznie trzy drzewa. Dla każdego stanowiska wybrano jedno drzewo o najlepszej korelacji ze średnią chronologią. Podobne podejście zostało zastosowane przez Koprowski i in. [2018]. Aby wybrać najbardziej reprezentatywne i odpowiednie drzewa do QWA, sprawdzono korelację wybranej próby z chronologią główną (wykluczając wybraną próbę). Dla stanowiska 1 najwyższa korelacja wybranej próby wyniosła 0,79 ($p < 0,05$), dla stanowiska 2 = 0,74 ($p < 0,05$), a dla stanowiska 3 = 0,77 ($p < 0,05$).

3.3.2. Przygotowanie preparatów mikroskopowych

Artykuł nr 2:

Trzy wybrane drzewa ścięto, a z każdego drzewa pobrano jeden krążek na wysokości pierśnicy. Z każdego dysku wybrano promień i podzielono go na drewniane kostki o wymiarach około 1×1×1 cm. Pozwoliło to na przygotowanie serii preparatów mikroskopowych obejmujących wszystkie słoje drzewa od rdzenia do kory. Preparaty mikroskopowe przygotowano zgodnie z metodologią zaproponowaną przez Schweingruber i in. [2006]. Cienkie (ok. 15 μm) przekroje poprzeczne zostały przygotowane przy użyciu mikrotomu GSL 1 core microtome [Gärtner, Nievergelt 2010], a następnie zabarwione safraniną w celu wybarwienia ścian komórkowych. Przekroje poprzeczne zostały następnie zamontowane przy użyciu Heft Histokittu i sfotografowane aparatem cyfrowym Canon DS126171 podłączonym do mikroskopu (Olympus BX41). Zdjęcia preparatów mikroskopowych zostały przetworzone przy użyciu oprogramowania Adobe Photoshop (wersja 22.5.5.) w celu zwiększenia kontrastu między ścianą komórkową a światłem komórki.

3.4. Analizy dendrochronologiczne

Na podstawie zsynchronizowanych szerokości słojów rocznych obliczono chronologie rzeczywiste (Tree-Ring Width - TRW). Aby wyeliminować długookresowe trendy przyrostowe oraz indywidualne cechy drzew, przeprowadzono standaryzację (indeksację) pomiarów według procedur opisanych przez Cook i in. [1990], które są zalecane przed podjęciem analiz dendroklimatologicznych. Standaryzacja została wykonana za pomocą pakietu dplR w programie R wersja 4.2.2 [Bunn 2008; R Core Team 2021], przy użyciu metody „spline" (*cubic smoothing spline*), gdzie długość krzywej 'spline' ustalono na 50 lat. Dla wszystkich serii pomiarów obliczono standardowe statystyki: EPS (*Expressed Population Signal*) i Rbar (*Interseries Correlations*). EPS wyraża siłę sygnału klimatycznego zawartego w szerokościach słojów [Buras 2017], natomiast Rbar informuje o jednorodności reakcji przyrostowych w grupie badanych drzew [Wigley i in. 1984; McCarroll, Loader 2004].

Tabela 1 Wartości wskaźników Rbar i EPS dla poszczególnych stanowisk.

Numer stanowiska	Nazwa stanowiska	Rbar	EPS	Lata	Liczba prób w chronologii
1	Barb	0.205	0.857	1847-2019	34
2	Bornesul	0.457	0.888	1864-2008	13
3	Borytuch	0.393	0.928	1847-1998	10
4	Cewi	0.422	0.954	1903-2021	42
5	Ciec	0.486	0.954	1904-2021	31
6	Ilawa	0.399	0.929	1944-2011	25
7	Jastarnia	0.5	0.92	1836-1998	18
8	Klin	0.415	0.955	1912-2021	32
9	Kudypy	0.345	0.811	1862-1998	15
10	Milomlyn	0.545	0.956	1854-2015	25
11	Mlynary	0.25	0.823	1908-1998	19
12	Mysz	0.407	0.954	1927-2021	43
13	Pborec	0.599	0.924	1876-2000	12
14	Potr	0.381	0.953	1938-2021	48
15	Resk	0.471	0.958	1924-2021	39
16	Ruciane	0.306	0.728	1887-1999	11
17	Siedlce	0.351	0.808	1891-1998	33
18	Skiern	0.49	0.957	1898-1998	38
19	Slowpn	0.264	0.836	1886-2005	21
20	Stegna	0.345	0.919	1862-1998	32
21	Walcz	0.401	0.929	1874-1998	35
22	Warc	0.354	0.946	1926-2021	46
23	Zytkiejmy	0.567	0.935	1879-2000	18

3.5. Analizy anatomiczne drewna

Artykuł nr 2:

W celu analizy parametrów komórkowych w każdym pierścieniu wybrano blok pięciu transektów komórek leżących w bezpośrednim sąsiedztwie. Liczba komórek w jednym transekcie zmieniała się z roku na rok i wahała się od 5 do 59 komórek na stanowisku 1, 29-90 komórek na stanowisku 2 i 24-82 komórek na stanowisku 3. Obliczenia dendroanatomiczne przeprowadzono w programie R [R Core Team 2021], R wersja 4.2.2 (2022-10-31 ucrt) przy użyciu pakietów. Pakiet tracheideR [Campelo i in. 2016] został użyty do przekształcenia surowych danych uzyskanych z analizy obrazu w tracheidogram w celu lepszej wizualizacji promieniowej zmienności wewnątrz pierścienia i uzyskania pomiarów parametrów: grubość ściany komórkowej (CWT), szerokość światła komórki (LD), szerokość przyrostu rocznego (RW), całkowita ilość komórek w przyroście (nTotal), drewno wczesne (EW) i drewno późne (LW). Do analizy EW i LW zdecydowano się wykorzystać względny procent drewna wczesnego (relEW) i drewna późnego (relLW), w celu łatwego porównania ze sobą przyrostów rocznych. Wykorzystano metodę opracowaną w pakiecie tracheideR przez Campelo i in. [2016].

3.6. Analizy dendroklimatologiczne

Analizy wpływu warunków klimatycznych na szerokość słojów przyrostów rocznych sosny zwyczajnej dokonano w programie R (Artykuł nr 1, 2 i 3). Analizie poddano wpływ sumy opadów atmosferycznych oraz średnich temperatur w oparciu o dane dobowe i miesięczne (Artykuł nr 1) oraz tylko miesięczne (Artykuł nr 2 i 3). Do analizy dobowych zmian klimat-przyrost użyto funkcji „daily response” z pakietu „dendroTools” w R [Jevšenak, Levanič 2018; Jevšenak 2019]. Aby zbadać związek z temperaturą dobową, na podstawie współczynnika korelacji Pearsona, wybrano przedziały czasowe 30 i 60 dni, a dla opadów 60 i 180 dni. Analizy przeprowadzone na danych miesięcznych opierały się na tych samych przedziałach czasowych co dane dobowe; wybrano miesiące najbliższe do dat danych dobowych (Artykuł nr 1). Do analizy danych miesięcznych użyto pakietu „treeclim” [Zang, Biondi 2015], korzystając z funkcji „dcc” i metody „bootstrap” do kalibracji związku między klimatem a przyrostem (Artykuł nr 1, 2 i 3).

Dane poddano testom statystycznym, takim jak współczynnik korelacji Pearsona (r), redukcja błędu (*reduction of error*: RE), współczynnik wydajności (*coefficient of efficiency*: CE) i pierwiastek średniego błędu kwadratowego (*root-mean-square error*: RMSE). Przeprowadzono metodę krzyżowej kalibracji i weryfikacji (*cross-calibration and verification*) [Briffa, K., Jones 1990; Lindholm i in. 2001], aby przetestować równania regresji. Analizowano okres od 1921 do 2019 roku. Niezależne i zależne zmienne, czyli serie przyrostów drzew, opadów i temperatur, podzielono na dwie grupy o równej długości (1921-1970 i 1971-2019). Jeden okres służył do kalibracji, a drugi do weryfikacji.

Na koniec wybrano lata ekstremalne za pomocą programu COFECHA 6.06P [Grissino-Mayer 2001] i porównano je z ekstremalnymi wydarzeniami meteorologicznymi w ostatnim stuleciu, wykorzystując klimatyczne dane dobowe i miesięczne (Artykuł nr 1).

4. WYNIKI

Artykuł nr 1:

Porównanie danych dobowych i miesięcznych:

Analiza wykazała istotną korelację między szerokością przyrostów rocznych drzew a opadami i temperaturą, zarówno w ujęciu miesięcznym, jak i dobowym. Istotne statystycznie korelacje dla opadów w ujęciu miesięcznym zanotowano w marcu, kwietniu i czerwcu, natomiast dla temperatury – w lutym i marcu, a negatywne dla września poprzedniego roku. Dane dobowe pozwoliły na bardziej precyzyjne określenie tych zależności, wykazując dla opadów najwyższe pozytywne korelacje dla okresu 60-cio dniowego (22. maja – 20. lipca) i 180-cio dniowego (7. lutego - 5. sierpnia). Dla temperatur najwyższe korelacje wykazano dla okresu 30-dniowego (21. lutego – 22. marca) i 60-cio dniowego (21. stycznia – 21. marca). Dane dobowe okazały się być bardziej precyzyjnym wskaźnikiem ekstremalnych zjawisk pogodowych, takich jak susze czy bardzo niskie temperatury, w porównaniu z danymi miesięcznymi, ponieważ dokładniej odzwierciedliły wpływ klimatu na wzrost drzew i szerokość ich słojów.

Ekstremalnie wąskie i szerokie słoje:

W badanym okresie (1856–2019) zidentyfikowano sześć lat charakteryzujących się ekstremalnie wąskimi słojami (1871, 1901, 1940, 1956, 1964, 2006). Zaobserwowano, że głównymi czynnikami ograniczającymi wzrost były niskie temperatury pod koniec zimy oraz niskie sumy opadów w sezonie wegetacyjnym. Nie odnotowano lat charakteryzujących się wyjątkowo szerokimi słojami.

Artykuł nr 2:

Zbadano wpływ nawożenia na wybrane parametry ekologiczne na trzech różnych stanowiskach. Dane podzielono na trzy okresy, w zależności od intensywności nawożenia terenu leśnego. Ponadto, wybrano dwie formy kontroli: stanowisko kontrolne nr 3, położone poza strefą Leśnej Oczyszczalni Ścieków, oraz okres wzrostu drzew przed wprowadzeniem ścieków (1971–1983).

Okresy nawożenia:

- Okres braku nawożenia (1971–1983): okres wzrostu drzew przed wprowadzeniem ścieków.

- Okres niskiego nawożenia (1984–1996): nawożenie obszaru mieszanką ścieków o niskim stężeniu biogenów. Średnie roczne stężenia: N – 195 mg/dm³, P – 32 mg/dm³, K – 318 mg/dm³.
- Okres wysokiego nawożenia (1997–2009): nawożenie obszaru mieszanką ścieków o wysokim stężeniu biogenów. Średnie roczne stężenia: N – 364 mg/dm³, P – 43 mg/dm³, K – 521 mg/dm³.

Porównanie stanowisk w różnych okresach:

- W okresie braku nawożenia na stanowisku 1 odnotowano pozytywny wpływ temperatury lutego i marca na całkowitą liczbę komórek w przyroście rocznym (nTotal). Na stanowisku 2, opady w okresie od maja do lipca miały pozytywny wpływ na szerokość przyrostu rocznego (RW), nTotal oraz szerokość światła komórki (LD).
- W okresie niskiego nawożenia na stanowisku 1 stwierdzono negatywny wpływ N na RW, podczas gdy P i K miały wpływ pozytywny. Na stanowisku 2, K miał negatywny wpływ na LD, a N oraz temperatura lutego i marca pozytywnie wpłynęły na grubość ściany komórkowej (CWT).
- W okresie wysokiego nawożenia na stanowisku 1, N miał pozytywny wpływ na LD i drewno wczesne (EW), natomiast P wykazywał negatywny wpływ na nTotal oraz drewno późne (LW). K miał silny negatywny wpływ na CWT, a opady w okresie od maja do lipca miały pozytywny wpływ na RW i nTotal.

Porównanie zmian w obrębie pojedynczego stanowiska:

- Na stanowisku 1, gdzie stosowano nawożenie, zaobserwowano istotny spadek RW oraz CWT pomiędzy okresem kontrolnym (przed nawożeniem), a okresem wysokiego nawożenia. Zwiększenie koncentracji składników odżywczych w ściekach prowadziło do zmniejszenia grubości ścian komórkowych (CWT). Zmniejszyła się również szerokość LD w miarę wzrostu stężenia składników odżywczych.
- Na stanowisku 2 odnotowano pogrubienie CWT w okresie niskiego nawożenia w porównaniu z okresem kontrolnym. Natomiast na stanowisku 3 nie zaobserwowano istotnych zmian w CWT.

Artykuł nr 3:

Zmiany temperatury i opadów w latach 1951-2019

W celu analizy zmian klimatycznych na przestrzeni lat, obliczono średnie roczne temperatury oraz sumy rocznych opadów dla trzech wybranych okresów: 1951-1973, 1974-1996 i 1997-2019. We wszystkich badanych lokalizacjach odnotowano wzrost temperatur, który wyniósł do 1,5°C. Porównując zmiany między pierwszym okresem (1951-1973) a drugim (1974-1996), wzrost temperatury wyniósł średnio 0,2-0,3°C, natomiast w trzecim okresie (1997-2019) zaobserwowano jej znaczny wzrost, wynoszący około 1°C, porównując do drugiego okresu.

W przypadku opadów, zmiany nie miały charakteru liniowego, a korelacje przestrzenne były trudne do uchwycenia. W niektórych lokalizacjach (np. stanowiska 1, 5, 15) zauważono postępujący spadek sum opadów, podczas gdy w innych (np. stanowiska 14, 22, 23) sumy opadów rosły. W kilku przypadkach suma opadów w drugim okresie była mniejsza niż w pierwszym, zaś w trzecim okresie wzrosła, osiągając poziom wyższy niż w pierwszym (np. stanowiska 2, 3, 18).

Aby zbadać wpływ klimatu kontynentalnego i oceanicznego w Polsce, dla każdego z okresów opracowano wykresy (heatmap) przedstawiające korelacje między szerokością pierścieni drzew a danymi klimatycznymi (temperatury miesięczne i sezonowe). W połączeniu z analizą dendrogramu, który grupuje lokalizacje w zależności od dominującego wpływu typu klimatu, uzyskano dodatkowe informacje na temat regionalnych różnic w odpowiedzi drzew na zmiany klimatyczne.

Okres 1951-1973

Najwyższa korelacja między szerokością pierścieni drzew a temperaturami występowała w zimie i wczesną wiosną, zwłaszcza w lutym i marcu, a czasem także w kwietniu. Stanowiska w zachodniej Polsce (Bornesul, Klin, Potr) nie wykazywały tej samej reakcji na temperatury co pozostałe stanowiska i były grupowane razem w dendrogramie, co sugeruje specyficzny wpływ klimatu w tej części kraju. W przypadku opadów nie wykazano jednoznacznego wzorca przestrzennego ani czasowego. Jedynie na stanowiskach Klin (styczeń) i Bornesul (luty) stwierdzono wyjątkowo silną korelację z opadami. Te same miejsca, wraz ze stanowiskiem Potr, reagowały także na opady letnie. W analizie dendrogramu nie zaobserwowano również wyraźnego podziału między wpływem klimatu kontynentalnego a klimatu oceanicznego.

Okres 1974-1996

W latach 1974-1996, w porównaniu z pierwszym okresem, w większości lokalizacji zaobserwowano zmniejszoną reakcję szerokości pierścieni drzew na temperatury zimowe i wczesnowiosenne. Największy spadek współczynnika korelacji wystąpił w zachodnich częściach Polski (Potr, Resk, Cewi, Klin), jak również na niektórych stanowiskach centralnych (Skiern, Milomlyn), a wymienione lokalizacje nie wykazały wyraźnego wzorca korelacji z opadami. Natomiast pozostałe stanowiska, rozciągające się od zachodniej po wschodnią Polskę, wykazały silną korelację z temperaturami w miesiącach zimowych i wczesnowiosennych (styczeń-kwiecień), szczególnie w okresie zimowym, gdzie wartości korelacji przekraczały 0,7. Wiosną korelacja była mniejsza, ale nadal istotna (powyżej 0,4). Zjawisko negatywnej korelacji między szerokością pierścieni drzew a temperaturą występowało częściej, choć w większości przypadków nie było statystycznie istotne.

W przypadku opadów nie zaobserwowano wyraźnego wzorca przestrzennego, jednak wyróżniają się dwie grupy o umiarkowanych wartościach korelacji (wartości współczynnika p w zakresie 0,3-0,5). Pierwsza grupa wykazała dodatnią korelację z opadami w lutym, bez wyraźnej zależności przestrzennej. Druga grupa obejmuje lokalizacje w Polsce Wschodniej (Mysz, Ruciane, Ciec, Siedlce), gdzie wystąpiła negatywna korelacja z opadami od stycznia do maja bieżącego roku, oraz września roku poprzedniego. Stanowiska te określono jako znajdujące się pod wpływem klimatu kontynentalnego.

Okres 1997-2019

W tym okresie wyraźnie zaznaczył się podział między wpływem klimatu kontynentalnego a oceanicznego. Lokacje wschodnie (Mysz) oraz centralne (Barb, Ciec) wykazywały dominujący wpływ klimatu kontynentalnego, podczas gdy zachodnia część kraju była pod wpływem klimatu oceanicznego. W całym kraju zauważono umiarkowaną do silnej korelację między temperaturą w marcu a szerokością pierścieni rocznych drzew. Miejsca na zachodzie Polski (np. Cewi, Warc, Resk) wykazywały również wpływ temperatury lutego na szerokość pierścieni.

Stanowiska położone blisko Bałtyku (Cewi, Warc, Resk) reagowały pozytywnie na zimowe i wiosenne temperatury, ale nie wykazywały wyraźnej reakcji na opady. W analizowanych lokalizacjach zaobserwowano negatywną korelację z temperaturą w lipcu, a większość miejsc wykazywała także negatywną korelację z temperaturami sezonu letniego. Na stanowiskach będących pod wpływem klimatu oceanicznego reakcja na temperatury zimowe była pozytywna, podczas gdy w miejscach o wpływie kontynentalnym wyraźniejsza była negatywna reakcja na temperatury późnej wiosny i lata. Pomimo braku wyraźnego wzorca w przypadku opadów, w regionie centralnej Polski (Barb, Ciec) zaobserwowano silny, pozytywny wpływ opadów lipca na szerokość pierścieni drzew.

5. WNIOSKI

Artykuł nr 1:

W badaniach dotyczących zależności między szerokością przyrostów rocznych drzew a warunkami klimatycznymi, stwierdzono istotny wpływ temperatury, szczególnie w okresie od lutego do marca, oraz opadów, zwłaszcza w marcu, kwietniu i czerwcu, na wzrost sosny zwyczajnej. Wyniki te są zgodne z wcześniejszymi badaniami przeprowadzonymi w różnych częściach Polski, wskazując na istotność wczesnowiosennych temperatur oraz letnich opadów deszczu w kształtowaniu się rocznych przyrostów. Warto jednak zauważyć, że zmiany klimatyczne, takie jak cieplejsze zimy oraz wcześniejsze nadejście wiosny, mogą modyfikować warunki wzrostu, przyspieszając moment, w którym istotnie zaczynają oddziaływać opady i temperatury. Zjawisko to prowadzi do intensywniejszego zaopatrzenia gleby w wodę już w okresie lutego i marca, co w efekcie może wpływać na dynamikę wzrostu sosny. Ponadto, stwierdzono, że klimatyczne dane dobowe precyzyjniej odzwierciedlają relację przyrost drewna - klimat, w stosunku do danych miesięcznych. Analiza lat ekstremalnych wykazała, że przyczyną ich pojawiania się było występowanie zarówno mroźnych zim, jak i braku opadów w kluczowych miesiącach wegetacyjnych, co znacząco wpływało na rozwój rocznych przyrostów drzew potwierdzając, że kombinacja niskich temperatur na początku sezonu wegetacyjnego oraz niedoboru opadów w okresie wzrostu jest kluczowa przy powstawaniu wąskich słojów. Pomimo spójności z wcześniejszymi badaniami, wyniki te podkreślają potrzebę dalszych analiz wpływu zmian klimatycznych na wzrost drzew, zwłaszcza w kontekście prognozowanych zmian klimatycznych. Badania takie zostały podjęte w artykule nr 3. Zrozumienie tych zależności jest niezbędne w celu lepszego zarządzania lasami i podejmowania skutecznych działań ochronnych w obliczu zmieniającego się klimatu. Wnioski te podkreślają również znaczenie stosowania danych dobowych w badaniach dendroklimatologicznych, które mogą zapewnić wyższą precyzję analiz i bardziej szczegółowe zrozumienie wpływu warunków klimatycznych na wzrost drzew.

Artykul nr 2:

Badania nad wpływem nawożenia na drzewostan sosnowy wykazały, że intensywne stosowanie nawozów, zwłaszcza w postaci dużych dawek azotu, fosforu i potasu, może prowadzić do istotnych zmian w strukturze komórkowej drzew. W szczególności, nawożenie miało negatywny wpływ na cechy komórkowe drzew w obrębie działki nawożonej (stanowisko nr 1), co objawiło się zmniejszeniem szerokości promienia rocznego (RW), średnicy światła komórek (LD) i grubości ścian komórkowych (CWT). Na stanowisku sąsiednim, które formalnie nie była nawożone, ale znajdowało się na terenie Leśnej Oczyszczalni Ścieków, zaobserwowano mniej wyraźne, jednak nadal istotne zmiany w niektórych parametrach komórkowych, co świadczy o migracji nawozów do pobliskich roślin.

Badanie wykazało, że w pierwszej fazie nawożenia (1984–1996) największy wpływ na przyrosty promienia rocznego miały nawozy bogate w azot i fosfor. Z kolei, w drugiej fazie nawożenia (1997–2009) te same pierwiastki wpłynęły na grubość ścian komórkowych oraz na zmiany w proporcji drewna wczesnego i późnego, chociaż w tym przypadku różnice były mniej wyraźne. Można przypuszczać, że zbyt wysokie stężenie nawozów w glebie prowadzi do tzw. suszy fizjologicznej. Choć drzewa były regularnie nawadniane, nadmiar składników odżywczych w glebie mógł zaburzyć ich zdolność do pobierania wody, co w konsekwencji doprowadziło do zmniejszenia szerokości przyrostów rocznych drzew i osłabienia ich kondycji fizjologicznej. Stwierdzono, że wzrost poziomu nawozów w glebie powoduje zmiany w strukturze komórkowej drewna, które są podobne do tych, jakie zachodzą w warunkach naturalnego stresu wodnego. Nawet przy wystarczającej ilości wody w glebie, nadmiar nawozów może ograniczać zdolność roślin do jej pobierania, prowadząc do stresu osmotycznego i osłabienia wzrostu.

Artykuł nr 3:

W wyniku przeprowadzonej analizy zmian temperatury oraz opadów w trzech różnych okresach (1951-1973, 1974-1996, 1997-2019) zaobserwowano istotny wzrost średnich rocznych temperatur, wynoszący w sumie około 1,5°C. Wzrost temperatury w tym czasie miał wyraźny wpływ na rozwój sosny zwyczajnej, zwłaszcza w okresach zimowych i wczesno-wiosennych, kiedy to wyższe temperatury sprzyjały przyrostowi pierścieni rocznych. W ostatnich latach zauważono osłabienie reakcji drzew na zimowe temperatury, co może sugerować, iż wyższe temperatury zimą zmniejszają ich pozytywny wpływ na wzrost wiosną, a szczególnie na wcześniejszą aktywację podziałów kambialnych. Zmienność odpowiedzi drzew w czasie pokazuje, jak dynamicznie zmieniają się interakcje między temperaturą a wzrostem sosny w ciągu ostatnich dekad. O ile w pierwszym okresie dominowały temperatury zimowe i wczesno-wiosenne, o tyle w ostatnich latach większego znaczenia zaczęły nabierać temperatury marca. Może to świadczyć o przesunięciu okresu krytycznego dla wzrostu w kierunku wiosny, co może być wynikiem zmieniającego się sezonu wegetacyjnego w odpowiedzi na ocieplenie klimatu. Wpływ opadów na wzrost sosny zwyczajnej nie był tak wyraźny, a dane rzadko wykazywały istotną statystycznie zależność. Pomimo tego, w trzecim okresie, zaobserwowano pozytywną reakcję wzrostu drzew na opady w czerwcu, szczególnie w regionach o klimacie kontynentalnym. Badania wskazują na istotne różnice w odpowiedzi na zmiany klimatyczne w zależności od regionu, z wyraźnym rozróżnieniem na obszary pod wpływem klimatu oceanicznego i kontynentalnego. Zmiany te podkreślają złożoność zależności między klimatem a wzrostem sosny zwyczajnej. Choć temperatura odgrywa kluczową rolę w kształtowaniu tempa wzrostu drzew, nie mniej ważne są czynniki lokalne, takie jak opady czy rodzaj gleby. Przemiany klimatyczne, w tym wzrost temperatury i zmiany w sumie opadów, mają znaczący wpływ na rozwój lasów sosnowych oraz ich zdolność do adaptacji w przyszłości. Aby dokładniej zrozumieć te procesy, niezbędne jest kontynuowanie badań, które umożliwią formułowanie precyzyjnych prognoz dotyczących przyszłego rozwoju lasów w kontekście zmian klimatycznych.

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7. ZAŁĄCZNIKI – PUBLIKACJE WCHODZĄCE W SKŁAD ROZPRAWY DOKTORSKIEJ

Artykuł nr 1

Waszak, N.; Robertson, I.; Puchałka, R.; Przybylak, R.; Pospieszyńska, A.; Koprowski, M. Investigating the Climate-Growth Response of Scots Pine (*Pinus sylvestris* L.) in Northern Poland. Atmosphere 2021,12,1690.

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Article

Investigating the Climate-Growth Response of Scots Pine (*Pinus sylvestris* L.) in Northern Poland

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Abstract: Research Highlights: This study used a 99-year time-series of daily climatic data to determine the climate-growth relationship for Scots Pine (*Pinus sylvestris* L.) growing in Northern Poland. The use of daily climatic data improved the calculated climatic response of the trees. Background and Objectives: It was hypothesised that daily temperature and precipitation data would more precisely identify climate–growth relationships than monthly data. We compared our results to a previous study conducted in the 1990s that utilised monthly precipitation and temperature data. Materials and Methods: The chronology construction and data analyses were performed using CooRecorder, CDendro and R packages (dplR, treeclim, dendrotools). Forty-nine cores from 31 trees were included in the final chronology. Results: The precipitation and temperature of March had the strongest influence upon ring-widths. Despite a statistically significant correlation between monthly temperature and ring-widths, reduction of error (RE) and coefficient of efficiency (CE) statistics confirmed that daily data better describe the effect of climate on tree rings width than monthly data. Conclusions: At this site, the growing season of Scots pine has changed with the observed association with precipitation now starting as early as February–March and extending to June–July.

Keywords: dendroclimatology; daily climate data; monthly climate data; tree rings

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1. Introduction

Scots pine (*Pinus sylvestris* L.) is one of the common tree species found in Central and Eastern Europe and is often used in dendroclimatological studies [1–4]. It is also found growing in the upland and mountainous areas of Western Europe [5], and its wider distribution extends to Northern Europe [6–8] and Eastern Siberia [9]. Dendroclimatological research in Poland using the ring-widths of Scots pine has been widely reported [4,10–15]. Several long-term pine chronologies were constructed for Poland [16–22] and for the neighbouring countries of Germany, Estonia and Lithuania [23–25]. The wide spatial distribution and existing ring-width chronologies highlight the potential for future research on this species. Tree rings in Poland can be a source of information about both hydroclimatic events, such as droughts and air temperature [2,13,15,26–30]. Some factors, such as frost or summer drought may have an immediate effect on ring width, whereas other factors, such as winter drought, may have a delayed effect on ring widths. The effect of different factors is seen as variations in ring size and structure [31] with droughts causing narrow rings [2,15,30]. Droughts are considered to be one of the most stressful factors for trees [32–34]. Research on the influence of different climatic factors on changes in the tree-ring widths in conifers has been carried out since the mid-20th century [35]. The observation of changes in annual tree growth under the influence of the climate, and the response of trees to a range of extreme climatic conditions in specific years is an increasingly widespread branch of science [36–38]. The widely observed climate changes in recent decades [39] incline us to undertake a deeper analysis and a closer look at the reactions of individual tree species to changes in pluvial and thermal conditions. The analysis of changes in annual tree growth in the context of past climatic events allows us to predict how current tree stands may react in the future [40]. In order to analyse changes in tree growth in relation to climate over the last one hundred and fifty years, records of meteorological data from weather stations are required. Such data are available, among others, in the format of daily and monthly observations. Due to the wide availability of monthly data, they are commonly used in dendroclimatological analyses [8,15], both for deciduous and coniferous species worldwide. Nowadays, daily data are used more often in such kind of analysis [41–44]. Daily data can explain climate–growth relations better than monthly data as tree growth does not take place at a monthly scale as it is a living organism in which life processes are constantly taking place [45]. While daily data can describe climate–growth relations more precisely, it was decided to compare the climate–growth responses using daily and monthly data. We used a continuous series of daily and monthly data from nearby meteorological stations for our study. Daily climatic data are much more challenging to access but are often considered a better option than gridded daily [46] and monthly data for dendroclimatological analysis [46–48].

The main aim of this paper was to study the relationships between the tree ring width index, called tree rings in the following text, and monthly and daily climatic data. Due to the fact that monthly data are the mean values of the daily data from 28–31 days and artificially divide the vegetation period into smaller time spans, daily data have the potential to be more reliable for reconstructing past climates. To investigate the potential for climatic reconstruction, the data set was divided into two periods: the calibration and verification periods. The use daily/monthly climate data with appropriate statistical tests allowed for more precise analyses of the potential for climatic reconstruction. Having long-time daily climatic data from meteorological stations, we have the exceptional chance for a more precise study of climate growth relationships on tree rings of Scots pine growing in the neighbourhoods of the meteorological station. We also hypothesised that daily air temperature and precipitation data are better for identifying climate–growth relationships and can also be used to reconstruct past climates. For this purpose, we used one of the longest daily climate data series for Poland, covering the period 1740–2019, together with long-living Scots pine located about 3 kilometres from the existing meteorological station. In this location, instrumental observations were initiated in 1740 with homogenous monthly series available since 1871 and continuous daily data since 1921. The results of this research could be applicable to the long chronologies constructed from historical buildings in the Toruń region [15].

As droughts are considered to be one of the most stressful factors for trees [32–34] and the extreme drought events and extreme drought years are becoming more frequent we hypothesised that the daily climatic data are better at identifying shorter duration extreme events. We determined the presence of extreme years from daily resolution data wherever they were available. We wanted to establish if the extreme years calculated from daily data differed from those based on monthly data. In our research, extreme years are defined as years in which extremely wide or narrow tree rings, late or early wood layers, were created.

2. Materials and Methods

2.1. Study Area

The study area covers a region located in the eastern part of Toruń Basin [49], 53°3′18.68′′ N; 18°32′30.26′′ E, in the Kuyavian-Pomeranian region, in Northern Poland, with a mean altitude of 65 m. The area is part of the Chełmno Lakeland Region and is located less than 5 km from the Vistula River. Water flows into the Vistula river system and further downstream into the Gulf of Gdańsk in the Baltic Sea. The study site is located in the northern part of the city of Toruń, covered by a fresh mixed forest dominated by Scots pine (*Pinus sylvestris* L.) and Pedunculate oak (*Quercus robur* L.). The site is a moderately fertile habitat, rather humid, with a low groundwater level and a relatively low sum of precipitation (the mean sum of annual precipitation for years 1961–2004 was 536 mm).

2.2. Climate Data, Sampling, Tree Rings Measuring

Climate data with daily and monthly resolution are available for Toruń for different periods, since 1740 (see [50]). The location of weather stations covering the years 1871–2019 in Toruń is shown in Figure 1. The changes in the location of the weather stations were the results of historical changes, including two World Wars as well as an urban expansion [49]. The earliest available continuous homogenised series of monthly precipitation and mean monthly temperature starts in the year 1871 (for details see [50]). Continuous series of both variables with a daily resolution are available since 1921. For this reason, tree growth-climate relationships, were studied using both daily and monthly data taken from the common period 1921–2019. For the period 1921–2019, the data were provided by the Institute of Meteorology and the Water Management-National Research Institute in Poland.

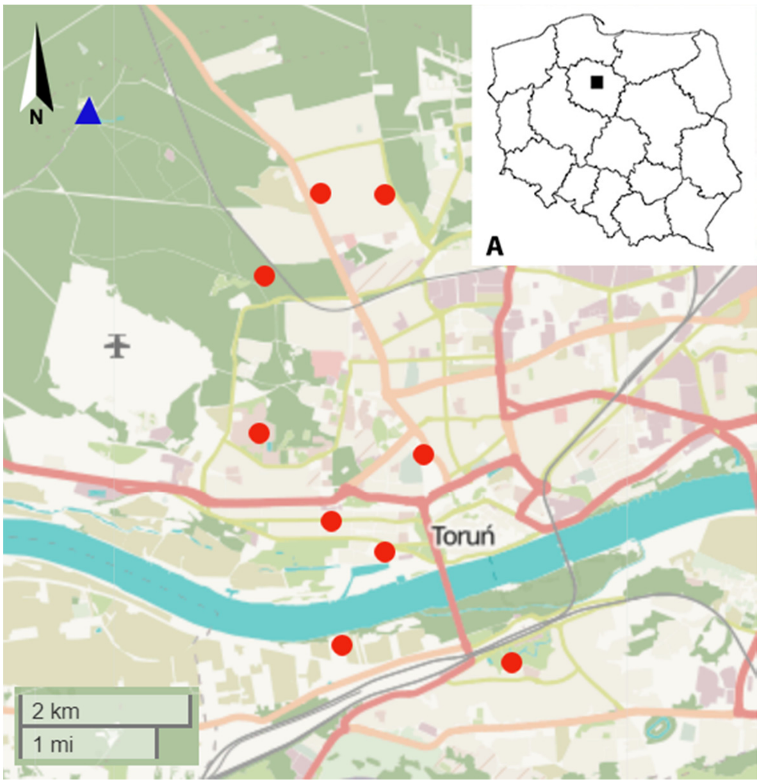

Figure 1. General location of the study area in Poland (A), location of meteorological stations in Toruń over the years 1871–2010 (dots, for more details see [50], location of the research site in the forest (triangle). Basic map and data from OpenStreetMap and OpenStreetMap Foundation © autorsOpenStreetMap.

In order to assess whether daily or monthly meteorological data were better at characterising the relationship with ring-widths, the sums of precipitation and average temperatures from the same meteorological station located in Northern Poland were compared. Tree cores were collected from about 175 years old Scots pines, with the oldest tree-ring dated to 1847. The tree ring width chronology was constructed with minimum samples depth of 20 over the period 1856–2019 (Figure 2). Samples were taken after the end of the growing season, during the late autumn and winter months in 2019. The trees selected for sampling were healthy, with a straight trunk and a regular crown. Some of the trees showed traces of resin extraction 50 years ago; however, it was still decided to utilise these samples due to their age and healthy appearance. Two samples were taken from each tree at breast height with a 5 mm diameter increment borer using standard techniques. In total 100 samples were taken from 50 trees. The cores were prepared for measurement using standard dendrochronological procedures [16]. All of the samples were air-dried, prepared with a sharp knife and scanned with 1200 dpi resolution using a standard scanner (Epson Perfection V700 Photo) to enhance the tree ring structure. CooRecorder 9.3.1 and the related CDendro 9.3.1 software (http://www.cybis.se; Accessed on 10 December 2021) were used to measure tree-ring widths to the nearest 0.01 mm. COFECHA 6.06P software [51] was used to check series intercorrelation, missing rings and detect possible dating errors. A smoothing cubic spline curve with a 50% wavelength frequency cut-off and response period of 32 years was fitted to each individual tree-ring widths series. Segments were examined in value of 50 years lagged successively by 25 years. The autoregressive model was applied to the time-series.

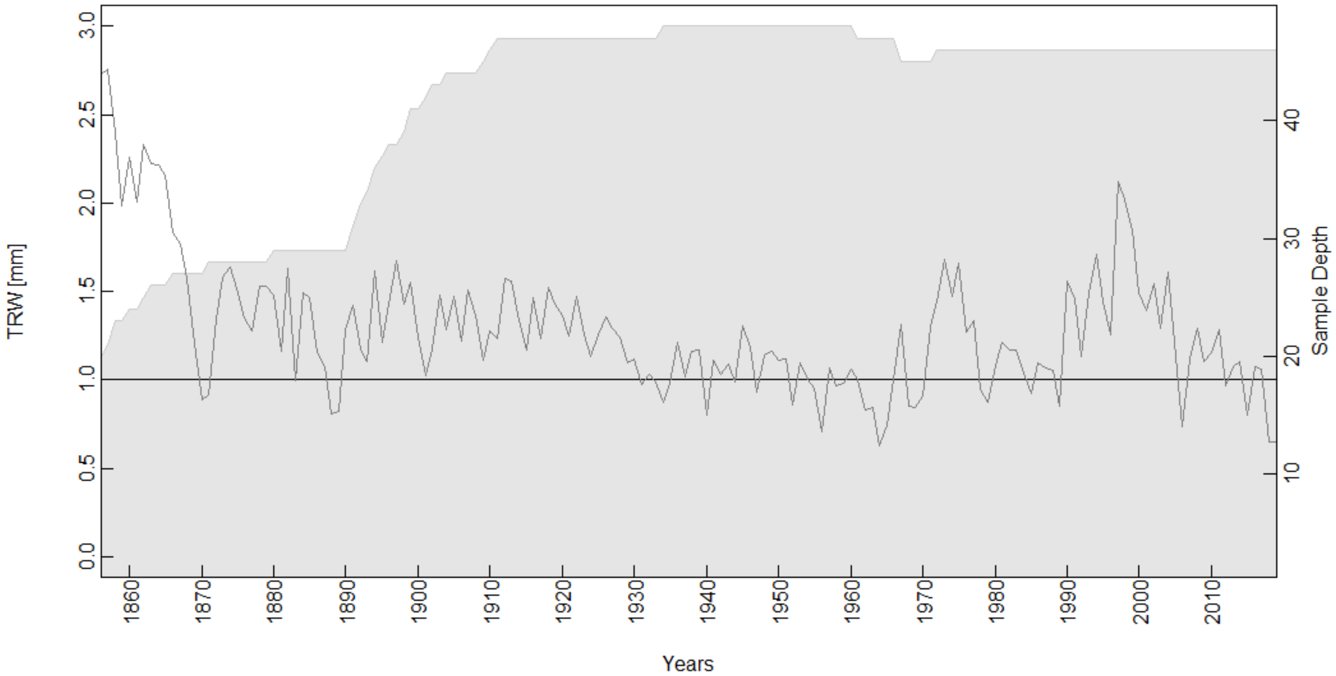

Figure 2. The tree ring width chronology and sample depth for years 1856–2019.

2.3. Chronology Building and Climatic Calibrations

A ring-width chronology was constructed from living trees covering the period 1856–2019. The tree ring widths of 49 cores from 31 trees were included in the final chronology. Some of the samples were rejected due to the presence of wood decay. Dendrochronological and statistical calculations were performed using R [52] with the application of selected packages: (i) the "dplR" [53] package was used to detrend the series by removing age-related growth trends and competition effects using Spline detrending method, (ii) the "treeclim" software [54] used a classical bootstrapped and Pearson correlation to calibrate the proxy–climate relationships and (iii) the "dendroTools" [55,56] package was used determine the optimal proxy–climate response window. Based upon the Pearson correlations over the period 1921–2019, a 30–60 day window was selected to study the relationship with daily temperature and a 60–180 day window was selected to study the relationship with precipitation (Table 1). Daily data rather than monthly data were used, which allowed a more accurate time intervals to be determined. The "daily response" function from "dendroTools" [55] R package was used, in which calculations are based on moving window which is defined with two arguments: window width (e.g., 30 days, 60 days and 180 days) and a location in a matrix of daily sequences of environmental data (precipitation, temperatures). The time intervals of 30 days, 60 days and 180 days were separated to obtain comparable information.

Table 1. The time intervals and calendar dates selected due to observed statistical significance of monthly values used to investigate the tree-climate growth responses.

Precipitation		**Temperature**	
Time Interval	**Period**	**Time Interval**	**Period**
60 days	22 May–20 July	30 days	21 February–22 March
180 days	7 February–5 August	60 days	21 January–21 March

For the analysis with daily precipitation values, periods of 60 and 180 days were selected due to observed statistical significance of monthly values, e.g., June–July or September–October for 60 days' time span each. Analyses performed on daily data were based on specific time intervals shown in Table 1 (e.g., 60 days: 22 May–20 July), which was selected on the basis of the dendrotools: daily response function [55] with the highest statistical significance. Analyses conducted on monthly data were based on the same time interval as for daily data, and those months were selected that coincided most closely with the dates of the daily data. So, for example, if the interval chosen for the daily data was 60 days: 22 May–20 July, then the interval was chosen for the monthly data was June and July. Using the same approach for temperatures, 30 and 60 day periods were selected (Figure 3). The chosen number of days were compared with the results of previous research conducted in this region [10–12].

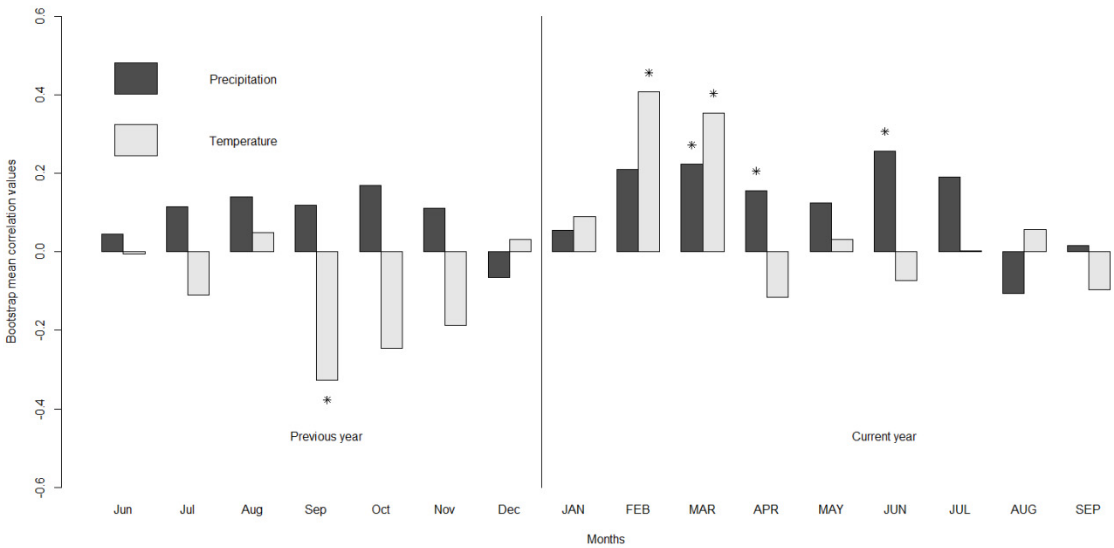

Figure 3. The relationships between the ring widths of Scots pine and climatic data over the period 1921–2019. Statistically significant months are marked with an asterisk * ($p < 0.05$).

The data were subjected to selected statistical tests, such as the Pearson correlation coefficient (r), reduction of error (RE), coefficient of efficiency (CE) and root-mean-square error (RMSE) tests, which were then compared with each other. The extreme years were selected and compared with extreme meteorological events in the last century. A cross-calibration and verification method [57,58] was carried out to test the regression equations. Both the independent and dependent variables, tree rings, precipitation and temperature series were divided into two groups of equal length (1921–1970 and 1971–2019). The time series was divided in two periods; one period was used for calibration with the other was used for verification. This approach enabled continuous data to be selected covering a long period without any gaps dividing the verification and calibration periods. As the selected time intervals were superior in calibration performance (Table 1), the relationship was calibrated and verified over two periods of equal length in order to examine the temporal stability [8]. For the calibration period, the Pearson correlation coefficient together with a statistical significance check (*p*-value) of 0.05 and 0.01 was performed. For the verification period several statistics were used including the reduction of error (RE), coefficient of error (CE) and root mean square error (RMSE) [31,59–61].

2.4. Extremely Narrow and Wide Tree Rings

The use of daily climatic data, gave the unique chance to check if extreme years calculated using daily data differ from those calculated using monthly data. The identification of extreme years using daily data enables an investigation as to whether the magnitude of results obtained from monthly data was diminished. The daily resolution climatic data records the exact days on which extreme weather events occurred. If they occur on the border of two months, they can be averaged and flattened during the analysis of monthly data. The aim of the analysis of extreme years was to find those years in which extremely narrow or wide tree rings were detected. The extreme years were selected and compared with meteorological data in the last century. Extreme years were determined with COFECHA 6.06P software using a procedure that averages the values inside the 50 year time window and 25 years lag time window [62]. The series reflects a residual time series that has been standardized to a mean of zero and a standard deviation of 1.0. Narrow rings are indicated by negative values and wide rings are indicated by positive values. Because values of −2.0 and +2.0 indicate departures from the mean by two standard deviations or greater, values of this magnitude are rare in the series and indicate very narrow and very wide rings, which are useful to confirm the independent cross-dating of the time-series.

3. Results

3.1. Daily and Monthly Data Comparison: Correlation of Tree Ring width Index to Climate Data

In order to check the association between tree-ring widths and both types of meteorological data (i.e., daily and monthly sums of precipitation and, daily and monthly average air temperatures), the same statistical tests (see Section 3.2) were used to investigate the correlation using data from period 1921–2019. Monthly data shows significant, positive correlations with precipitation in March (r = 0.22, $p < 0.05$), April (r = 0.16, $p < 0.05$) and June (r = 0.26, $p < 0.05$), while for temperature in February (r = 0.40, $p < 0.05$) and March (r = 0.35, $p < 0.05$) and negative effect in previous September (r = −0.33, $p < 0.05$) (Figure 3). Using daily data, for precipitation 60 days period the highest positive correlation was noted between 22nd of May and 20th of July (r = 0.329, $p < 0.05$) for 180 days between 7th and between February and 5th of the August (r = 0.386, $p < 0.05$). For temperature for 30 days between 21st of February and 22nd of March (r = 0.413, $p < 0.05$), for 60 days between 21st of January and 21st of March (r = 0.414, $p < 0.05$) (Table 1).

3.2. Monthly Climate Data

All time intervals (30, 60 and 180 days) for calibration period A (1921–1970), yielded significant ($p < 0.02$) reconstruction skills both for precipitation and temperature (Table 2). For calibration period B (1971–2019) only temperature data yielded significant ($p < 0.01$) reconstruction skill (Table 3). For precipitation data, both 60 days and 180 days intervals appeared to be insignificant but also resulted in the lowest correlation r $\leq$ 0.22. For calibration period A (1921–1970), RE and CE verification statistics yielded negative values for precipitation and acceptable RMSE values [57]. Both 30 days and 60 days' time intervals for temperature data showed acceptable results for the RE statistic and slightly negative values for CE, the RMSE test was very good with values below 1 [63]. For calibration period B (1971–2019), verification statistics of RE and CE tests yielded a reasonable model for precipitation data but poor results for the RMSE test. For temperature values, the RE test yielded a reasonable model, but the CE test results yielded negative values. The RMSE test yielded low values, below 1.3.

Table 2. Results of statistical tests for daily and monthly data in calibration period A: calibration period: 1921–1970 and verification period: 1971–2019. Statistical significance at level * $p < 0.02$, ** $p < 0.01$.

	Calibration Period A		Verification Period		
	1921–1970		1971–2019		
		r	RE	CE	RMSE
	precipitation				
daily	60 days	0.54 **	0.07	0.01	1.24
monthly		0.52 **	−0.04	−0.04	8.49
daily	180 days	0.47 **	0.07	0.05	0.44
monthly		0.50 **	−0.04	−0.04	5.19
	temperature				
daily	30 days	0.52 **	0.04	−0.39	3.14
monthly		0.54 *	0.17	−0.01	0.81
daily	60 days	0.42 **	0.17	−0.23	1.11
monthly		0.44 *	0.15	0	0.75

Table 3. Results of statistical tests for daily and monthly data in calibration period B: calibration period: 1971–2019 and verification period: 1921–1970. Statistical significance at level * $p < 0.02$, ** $p < 0.01$.

	Calibration Period B		Verification Period		
	1971–2019		1921–1970		
		r	RE	CE	RMSE
	precipitation				
daily	60 days	0.25	0.27	0.08	0.58
monthly		0.20	0.10	0	17.38
daily	180 days	0.33 *	0.20	0.17	0.35
monthly		0.22	0.10	0.07	10.97
	temperature				
daily	30 days	0.33 *	0.17	−0.16	3.05
monthly		0.38 **	0.21	−0.06	1.28
daily	60 days	0.42 **	0.16	−0.16	1.08
monthly		0.30 **	0.16	−0.15	1.28

3.3. Daily Climate Data

All time intervals (30, 60 and 180 days) for calibration period A (1921–1970) yielded significant ($p < 0.01$) reconstruction models both for precipitation and temperature. Additionally, almost all-time intervals for calibration period B (1971–2019) yielded significant ($p < 0.02$) reconstruction models besides the 60 day interval for precipitation which appeared to be insignificant but also resulted in the lowest correlation r = 0.25. Verification statistics were performed resulting in a reasonable model for RE test for both types of meteorological data. CE test yielded reasonable models in 1921–1970 and 1971–2019 calibration periods for precipitations but had a slightly negative value in 1921–1970 and 1971–2019 calibration periods for temperature. For both 1921–1970 and 1971–2019 verification periods, RMSE value was low and close to null for precipitation showing even values below 0.6.

3.4. Daily Climate Data vs. Monthly Climate Data

During the calibration period 1921–1970, the association between ring widths and, daily and monthly data were similar. The precipitation data showed a similar correlation with the width of tree rings as the temperature data. However, the situation was very different when the RE, CE and RMSE statistics were calculated. Analysing the results based on monthly precipitation data, the calculated RE and CE values were slightly negative, and the RMSE indicator was far higher than the results based on daily data. For temperature, the results were comparable, which means that results for RE were positive numbers both for daily and monthly data, while for the CE values were negative numbers both for daily and monthly data and, RMSE values were similar.

During the calibration period 1971–2019, the association between ring widths and, daily and monthly data, were not similar. In most cases, the association between ring widths and precipitation was not significant ($p > 0.05$). For temperature, the results of RE, CE and RMSE tests were comparable, which means that results for RE were positive both for daily and monthly data, for CE were negative numbers both for daily and monthly data and the RMSE values were similar.

3.5. Extremely Narrow and Wide Tree Rings

Extreme years analysis was performed on time span of 172 years, from 1856 to 2019. Six years with extreme rings width were found. Analysis of extreme ring widths revealed the occurrence of extremely narrow rings in 1871, 1901, 1940, 1956, 1964 and 2006. In these years, the residual values of the master dating series were, at least, below −2.0. There were no results higher than +2.0. The highest result of ring width occurred in 1997 and achieved a value of 1.981, which showed that there were no extreme positive years interpreted as exceptionally wide rings. Extreme years were compared with climatic data and it was observed that the main factors limiting growth were low temperature at the end of winter and a low sum of precipitation during the vegetation season. For example, in the year 2006 mean temperature from 21 January to 21 March was −4.3 °C and the sum of precipitation from 22 May to 20 July was 56.5 mm (Table 4). Climatic data showed extreme values for both temperature and precipitation, presenting exceptionally cold winters as well as droughts in the vegetation period of the plants. Years of extremely low growth rate were analysed and these pointer years were attributed to cases in which severe winters were followed by spring-early summer droughts. However, the question arises: were there other years with similar weather conditions which were not associated with significant growth reduction? There was not observed similar weather conditions in other years, when both temperatures at the end of winter and sum of precipitation during the vegetation season were low. The plot of minimum winter temperatures (December–February) and May–July precipitation constructed for the whole period (1921–2019), based on daily data, answer this question (Figure S1 in Supplementary Materials; Accessed on 14 December 2021). No other extremely narrow or wide annual increments were noted.

Comparing mean temperature and precipitation in extreme years obtained from daily and monthly data, the difference in values obtained is clearly visible (Table 4). In each case, the values differ significantly and are over- or underestimated irrespective of the selected period. These results demonstrate that daily data are more precise indicators for extreme weather events, such as periods of drought or extremely low temperatures, than monthly data.

Table 4. Climate conditions in the extreme years. In years with missing daily data, monthly data were used. Grey fields-monthly data. White fields- daily data.

Extreme Year	Mean Temperature (°C)				Precipitation Total (mm)			
	30 Days		60 Days		60 Days		180 Days	
1871	2.8 (March)		−2.3 (February–March, extreme February = −7.4)		230.8 (June–July)		292.2 (February–July)	
1901	1.0 (March)		−2.7 (February–March)		22 May–20 July	55.1	186.9 (February–July)	
					May–July	60.7		
1940	21 February–22 March	−2.4	−6.0 (February–March)		22 May–20 July	69.8	7 February–5 August	183.7
	February–March	−6.0			May–July	105.9	February–August	225.3
1956	21 February–22 March	−3.2	21 January–21 March	−6.6	22 May–20 July	102.3	7 February–5 August	201.4
	February–March	−5.6	January–March	−4.0	May–July	282.9	February–August	306.3
1964	21 February–22 March	−4.7	21 January–21 March	−3.7	22 May–20 July	79.2	7 February–5 August	160.3
	February–March	−3.3	January–March	−3.3	May–July	111.8	February–August	251.1
2006	21 February–22 March	−3.4	21 January–21 March	−4.3	22 May–20 July	56.5	7 February–5 August	198.3
	February–March	−1.4	January–March	−3.6	May–July	95.4	February–August	335.9
1871–2019	0.3 (February–March)		−0.6 (January–March)		190.1 (May–July)		275.2 (February–July)	

4. Discussion

One of the aims of this paper was to re-investigate the observed relationship between ring widths with monthly and daily climatic data for the Toruń region [10]. We constructed a ring-width chronology and updated the daily and monthly climate data [50]. In Poland, the relationship between monthly climate data and the ring-widths from the long Scots pine chronologies has already been established at several locations. For stands in Southern Poland in the Dąbrowa Tarnowska Forest Distinct, Feliksik 1988 [64] reported that the trees responded to winter temperatures, which was confirmed by stands in the Świętokrzyski National Park that were influenced by the temperatures of January to March and precipitation from April to August [65]. Analyzing Scots pine stands in South-Western Poland in the lowlands [66], and the Sudety Mountains [67,68] it was found that the temperatures for February–March and summer precipitation influenced growth. Many dendroclimatological analyses with chronologies of more than 100 years have been made for Northern [10,11] and North-Western Poland [69] where they found that February–April temperature and June–July and December precipitation primarily influenced ring widths. By analysing new material, we found a significant climate signal for February–March and previous September temperatures, as well as March–April and June precipitation (Figure 3). In the case of monthly temperatures, the results confirm previous studies [10], as well as the relationships observed for pine stands in southern Poland [66–68]. In these studies the significance of the effect of precipitation on growth was determined for the summer months, June–July, both in the south and north of Poland [10,11,65,66,68]; only for the Świętokrzyski National Park was the relationship with precipitation from April to August significant [66]. Repeating the tree rings width-climate correlation study after 20 years, we find a significant climate signal for precipitation for March, April and June (Figure 3). At the same time, the value of the correlation coefficient for precipitation is similar for February and July. A previous study revealed the significance of precipitation in February, which is reported elsewhere for other conifer species, spruce and larch in Northern Poland [70]. Cedro and Lamentowicz 2011 [71] analysed the increment-climate correlation for pines growing on the edge of a swamp, in Northern Poland, defining their climate signal as typical for this species, indicating the significance of the effect of precipitation in February. Our results confirm previous studies, but it is worth noting the influence of both March precipitation and temperature.

In Northern Poland, with the current climatic changes, warmer winters and earlier spring, intensive potential thaw and rainfall begin as early as February-March resulting in a more intensive substrate water supply than before [72]. The change in climatic conditions may cause a change in growing conditions, accelerating the period of rainfall significance and starting as early as February–March and extending to June–July. Due to rising winter temperatures and changes in evapotranspiration pattern the effect of climate change on individual species can be either positive or negative, depending on the site conditions and regional climate changes [73]. Responses simulated with 70 different models of climate change variations vary considerably, which is adding considerable uncertainty [74]. It is crucial due to the fact that Scots pine trees are the main forest-forming species in the European lowlands, Northern Europe, and Northern Asia.

Using daily measurement data from the nearby meteorological station we elucidated a clear relationship between ring widths and climate. It is the first time for Northern Poland that the proxy–climate relationship has been investigated with daily climate data. In general, we found in the years 1921–2019 the highest correlation for temperature between 21 February to 22 March and 21 January to 21 March depending on a time span. For precipitation, we found the highest correlation from 22 May–20 July and 7 February–5 August (Table 1). The comparable results were presented by Liang et al. 2013 [75], who analysed Scots pine in North-Eastern Germany. The results are comparable for precipitation, where the authors indicate the period with the highest climate–growth correlation on 26 May–18 June and 29 June–25 July, which is in agreement almost every day with our results falling on 22 May–20 July. However, in the case of temperature influence the results differ considerably, as Liang et al. 2013 [75] indicates the interval 24 March–23 May, while in the case of the site analysed by us, in Northern Poland, it is the period 21 January–21 March or 21 February–22 March depending on the selected time interval. It is worth noting, however, that the sites, although quite similar, are under the influence of different climatic conditions, with the German site under the influence of an oceanic climate, characterised by milder climatic conditions, and the Polish site under the influence of a transitional climate with a colder winter and more variable climate. In addition, the study is separated by a period of almost 10 years, during which a number of warm winters occurred. This may partly explain the discrepancy in results, but further research into this phenomenon is needed. Studies using daily data have also been performed by Pritzkow et al. 2014 [76] on Scots pine in Northern Sweden, at the Arctic Circle, and by Kaczka et al. 2017 [44] on Norway spruce in the Tatra Mountains in Southern Poland. Kaczka et al. 2017 [44] indicates that the highest temperature relevance for tree growth occurs between Jun 9th and Jul 19th while Pritzkow et al. 2014 [76] determines it between Jul 7th and Jul 29th, which in both cases highlights the relevance of summer temperatures on tree growth, where in Northern Poland we define the early spring period as thermally relevant.

Seo et al. 2008 [77], Kaczka et al. 2017 [44], Nagavciuc et al. 2019 [78] reported that the use of daily climatic data was more reliable as there was a higher correlation with ring-widths. Moreover, they found that the flexible time interval based upon days rather than months adapted to the vegetation period of plants better. In our paper, we expanded upon this initial research and used additional statistical tests, such as RE, CE and RSME, to investigate the temporal stability of this relationship. The data presented in Tables 2 and 3 demonstrate that the correlation coefficient (r) alone is not sufficient to conclude that there is a stable association between the ring widths of Scots pine and precipitation at this site. Even though the correlation (r) with ring-widths was sometimes lower for daily data ($r = 0.47$) than for monthly data ($r = 0.50$) it yielded, significant RE and CE values (>0) and a very accurate RSME response (<1) (Table 2). The equivalent tests using monthly precipitation data were not temporally stable (Table 2). These results highlight the importance of calculating RE, CE and RSME values to investigate the temporal stability of the climate response [63]. Consequently, existing dendroclimatological research based solely upon p-values may not be as reliable as once thought. It is recommended that the temporal stability of tree-climate growth responses should always be investigated [61].

Moreover, it was found that daily climatic data were statistically more reliable, although they may have a slightly lower correlation coefficient compared to monthly data. In some cases, results based on monthly data, despite a high correlation coefficient $r > 0.50$ and a statistical significance at p-value <0.01, RE and CE values demonstrated the lack of temporal stability. For daily data during the calibration period 1921–1970, the value of the correlation coefficient was similar for temperature and precipitation data, but the value of the correlation coefficient was higher for precipitation. In addition, for precipitation, the other statistical tests are better because both RE and CE values were positive. During the calibration period 1971–2019 the correlation coefficient was higher for temperature data with $r = 0.42$; however, the results of RE, CE, RMSE tests are more reliable for precipitation data for a six-month period (180 days). For monthly data, the precipitation results for the calibration period 1971–2019 were statistically insignificant ($p > 0.05$), so the analysis of the other statistical tests was futile. For the calibration period 1921–1970, the results for the precipitation data had a high correlation coefficient $r > 0.50$ but were statistically unreliable because the results of RE and CE tests were negative. The interpretation of these results was based upon previous research in life sciences [63,79,80].

In addition, it was noted that regardless of whether daily or monthly data were used for the analysis, the correlation between the annual tree rings width and temperatures or precipitation is significantly lower $0.20 < r < 0.38$ in calibration period B (1971–2019) than in calibration period A (1921–1970) where it is in the range $0.44 < r < 0.54$. A similar correlation has been observed among other conifers in the northern hemisphere, also since 1970, and has been described as the 'divergence problem' [81]. The 'divergence problem' was also observed in other tree ring proxies such as blue intensity [82] and stable isotopes [83].

Extreme Years

Analysis of extreme ring widths revealed the occurrence of extremely narrow rings in 1871, 1901, 1940, 1956, 1964 and 2006. A negative effect of cold winters in 1940 and 1956 was observed in southern Germany [84]. Neuwirth et al. 2007 [85] noticed the year 1956 as a strong negative effect in fields of Central Europe lowlands, including northern areas in Poland due to a very warm spring combined with below average rainfall in at least one month in the first half of the growing season. They also point the year 1964, as a negative for tree stands in Northern and Northern-East Germany. Since the results of our research showed that daily data are better suited for dendroclimatological analyses (Tables 2 and 3), daily resolution data were used to analyse extreme years wherever they were available (Table 4). Where daily data were not available or did not cover the whole range of time intervals, monthly data were used. It turns out that in the case of temperature data, in all cases, the average temperature values for the winter months (60 days) differed significantly from the multi-annual average (−0.6 °C), reaching the average temperature value for that period even −6.6 °C. In the case of precipitation data, in all years except 1871, the average sum of precipitation for the selected periods in each case was significantly lower than the multi-annual average over the 1871–2019 time period. Although 1871 had a higher than the average sum of precipitation, the record low temperatures of February had an extremely negative impact on the formation of the annual tree ring and caused its exceptionally low growth. For each of the five next extreme years there was an exceptional combination of high frosts in winter and drought in the growing season. The combination of these two climatic factors in the indicated years significantly influenced the formation of exceptionally narrow tree rings in the examined Scots pine trees in Northern Poland. All the extreme years are confirmed by Pospieszyńska et al. 2013 [86], who, on the basis of instrumental measurements, analysed the extreme climatic conditions in the years 1871–2010 in the research region. They confirm the occurrence of exceptionally low air temperatures and exceptionally small amounts of precipitation in those extreme years (Table 5). Przybylak et al. 2020 [30] discussing the occurrence of droughts in Poland, lists the years 1956, 1964 and 2006 as years with low annual rainfall. Zielski 1997 [10] indicates the occurrence of a very cold winter in 1940 and a combination of harsh winter and very dry year in 1956 and 1964. Koprowski et al. 2012 [15] also mention these years as indicator years for Scots' pine. Based upon this evidence, we conclude that the extreme years' analyses conducted from daily climatological measurements do not differ from the results based on monthly data and gives typical results for the area of Poland. Furthermore, all of the above extreme years are confirmed by specific climate events recorded in the instrumental measurements.

Table 5. Pointer years and their explanations.

Pointer Years	Zielski et al., 1997 [10]	Pospieszyńska and Przybylak, 2013 [86]	Przybylak et al., 2020 [30]
1871		very cold year	
1901		very dry year	
1940	very cold winter	very cold year	
1956	harsh winter, very dry year	very cold year	low precipitation
1964	harsh winter, very dry year	very dry year	low precipitation
2006		very warm summer and autumn	low precipitation

5. Conclusions

In the study, the growing season of Scots pine has changed with the observed association with precipitation now starting as early as February–March and extending to June–July. These phenological changes indicate that the climate–growth response of Scots pine is not stable in this region. Despite a statistically significant correlation between monthly temperature and ring-widths, reduction of error (RE) and coefficient of efficiency (CE) statistics confirmed that daily data better describe the effect of climate on tree rings width than monthly data. A change in growth patterns can cause far-reaching changes in the structure of tree-stands and affect the economic market, which has serious implications as Scots pine trees are the main forest-forming species in the European lowlands, Northern Europe, and Northern Asia.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/atmos12121690/s1, Figure S1: Minimum winter temperatures (December–February) and May–July precipitation over the period (1921–2019).

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MDPI

Supplementary Materials: Investigating the Climate-Growth Response of Scots Pine (Pi-nus sylvestris L.) in Northern Poland

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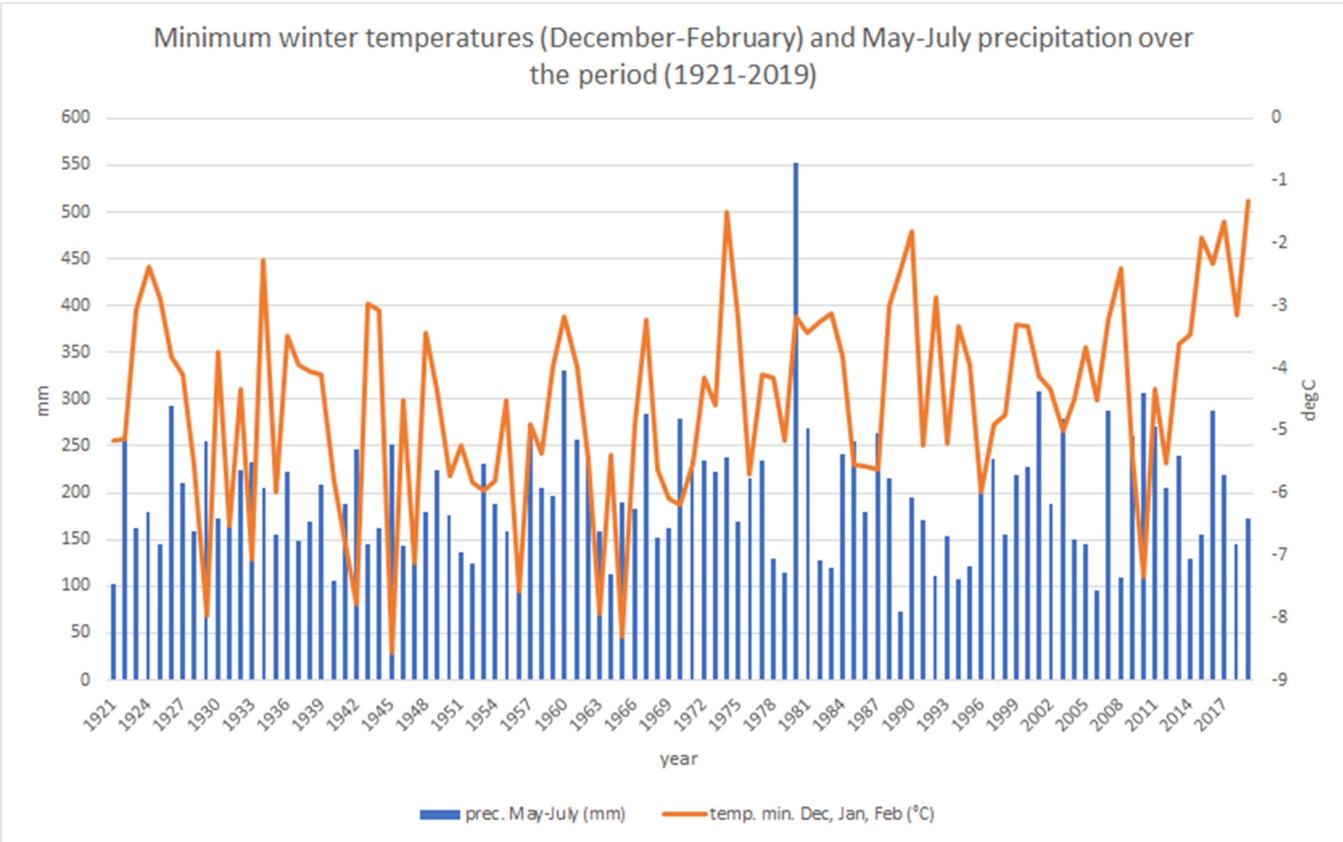

Figure S1. Minimum winter temperatures for months December-February (marked by orange line and expressed in degrees celcius) and May-July precipitation (marked in blue lines and expressed in mm) over the period (1921–2019), based on daily data.

Artykuł nr 2

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Fertilisation with potato starch wastewater effect on the growth of Scots pine (*Pinus sylvestris* L.) forest in Poland

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ABSTRACT

Fertilisation is often used to increase plant productivity in agriculture but has also been used in forestry. In our study, Scots pine forest growing in a nitrogen-poor environment was fertilised with NPK post-production wastewater from a potato starch factory. Our research aimed to investigate the dependence of tree growth on different NPK concentrations. Cell characteristics such as cell wall thickness (CWT), lumen diameter (LD) and tree-ring features such as ring width (RW), total number of cells in annual growth (nTotal), earlywood (EW) and latewood (LW) were investigated. Twenty-six years of regular fertilisation of the forest with different doses of wastewater rich in NPK elements have affected the anatomical structure of Scots pine trees. It is presumed that the reduction in CWT and LD on the fertilised site was due to deficiencies in plant water conductivity, which may have occurred due to physiological drought. The influence of nitrogen on unfertilised site from the wastewater area could contribute to the CWT thickening. The results confirm that the use of NPK in excessive doses is detrimental to trees' conductive system.

Introduction

Forest fertilisation experiments have been conducted worldwide (Fox et al., 2007; Moller, 1992), mainly to increase productivity by enhancing the average wood biomass per unit area (Smethurst, 2010). However, results from these experiments have been mixed, with some studies reporting increased growth (Fox et al., 2007; From et al., 2015; Haveraaen and Frivold, 2015; Jacobson and Pettersson, 2001; Moller, 1992; Nilsson et al., 2021), while others found no significant effect or even reduced growth (Kytö et al., 1999; Seftigen et al., 2013; Wallace et al., 2007). Forest soil enrichment has become a common practice in northern Europe to increase tree biomass and gain economic benefits (Lindkvist et al., 2011). Nitrogen (N) is considered to be a major growth-limiting factor in many northern forests (Hedwall et al., 2014), including those with podzolic soils found in the study area in Poland (Chojnacka-Ożga et al., 2022). Those experiments have been carried out with varying intensity in different northern countries, usually with positive results in the form of increased tree biomass (Balster and Marshall, 2000; Hedwall et al., 2014; Lindkvist et al., 2011). Stand fertilisation is known to have an almost immediate effect on tree growth and can be applied even in mature forests (Jacobson and Pettersson, 2010; Nohrstedt, 2001). The efficiency of soil enrichment in relation to the application rate is therefore strongly related to the nutrient demand and growth potential of the stand. It has been assumed that the effect on production decreases with repeated fertilisation (Jacobson and Nohrstedt, 1993), but (Jacobson and Pettersson, 2001) and (Pettersson and Högbom, 2004) found that while repeated, it maintained or even increased the effect of biomass growth, at least at longer intervals between nutrient supply. Sometimes additional growth was obtained when N was applied at relatively high and frequent rates and with phosphorus (P) and potassium (K) (Albrektson et al., 1977; Dralle and Larsen, 1995; Harrington and Wierman, 1990; Tamm et al., 1999). The reason for

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supplying forests with nutrients may not only be to increase yields but also to dispose of post-agricultural waste which was the case in the Iława forest area (Chojnacka-Ożga et al., 2022; Ciepielowski et al., 1999; Koprowski et al., 2015).

The sustainable management of post-production waste is a serious environmental issue. The potato processing industry requires large amounts of water. Depending upon the starch content of the potatoes and the techniques employed, the processing of potatoes typically requires 8–17 litres of water per kilogram of potato (de Haan and Van de Ven, 1973; Peters, 1972; Van Hung et al., 2006). The vast majority of polluted wastewater originates from starch production. These waters typically have a high chemical oxygen demand with high levels of N and P. The large volumes of wastewater generated can be problematic because, according to current legislation, the municipal wastewater system should not be used to discard such a large volume of waste. Some of the methods used to treat starch wastewater include biochemical treatments, biogas fermentation, adsorption, air flotation, flocculation, precipitation, sedimentation and recently developed combined treatments (Bouchareb et al., 2021; Cai et al., 2019; Wu et al., 2016).

In the past, an agricultural approach was adopted in Poland to dispose of this nutrient-rich wastewater including the irrigation of meadows (Hawelke and Sokołowski, 1999) and a forest located near a processing plant (Ciepielowski et al., 1999). It was thought that this approach would solve the problem of waste treatment and at the same time have a positive effect on the growth of plant biomass within the irrigated ecosystems. As the forest in the vicinity of the starch factory in Iława grows on the relatively nutrient-poor sandy soils, it was expected to increase tree biomass and improve stand productivity, as the potato starch effluent is rich in elements such as N, K and P, hence the expectation that it could also be used to improve the nutritional status of forest stands. Previous studies have shown that pine forests should not be irrigated with wastewater from potato starch factories, as this wastewater can damage trees within a few years (Peters, 1972). Nevertheless, these results were not considered, and contrary to these findings, wastewater with a high starch content was applied in the Iława Forest District in the years 1984–2012.

In the case of Iława, previous studies have shown that high-effluent rates reduced biomass (Gumnicka, 1999), and potato starch effluent reduced photosynthetic efficiency and disrupted Scots pine growth (Koprowski et al., 2015). A more recent study in the same forest also found that an increase in the concentrations of NPK elements in post-production wastewater decreases the radial growth of trees (Chojnacka-Ożga et al., 2022).

As previous studies based on rings-width measurement showed a decrease in radial growth, it was decided to investigate which anatomical features had changed in the rings due to the application of different amounts of wastewater, which, when overused, can lead to physiological drought in plants. The reason for water limitation in plants can vary, from lack of precipitation, soil type specifics or over-enrichment (Ward et al., 2015) and as a result can lead to disturbances in plant growth. Other studies with pine (Ward et al., 2015) showed that nutrient supply intensifies drought stress by decreasing water use and stomatal conductance of loblolly pine in a mid-rotation fertilisation experiment. (Song et al., 2022) found that climate-induced changes in the anatomical structure of Chinese red pine tree rings occur mainly in earlywood rather than in latewood. Frequent severe droughts in dry areas may induce Chinese red pine to form smaller lumens and thicker cell walls to survive.

Surprisingly, from the perspective of the wood industry, a lower growth rate may affect wood quality, e.g., tracheid properties, in a positive way (Mäkinen et al., 2002a, 2002b; Saranpää, 2003). As (Jaakkola et al., 2006) note, wood properties determine the suitability of wood as an end product in the pulp and paper industry, wood panel industry and solid wood production. Tracheid properties express the density of the wood, which is widely used as a measure of wood quality (e.g. (Panshin and de Zeeuw, 1980; Saranpää, 2003)). Because the enrichment of coniferous forests is currently used worldwide to increase wood production (Augusto and Boča, 2022; Durand et al., 2020; Jaakkola et al., 2006; Ward et al., 2015), any research that increases knowledge of wood cell growth, especially of species highly used in forest plantations such as Scots pine, can contribute to a better understanding of their growth mechanisms and therefore more efficient management. Despite the growing interest in cell anatomy in dendrochronology, little is still known about interpreting the variability in cellular anatomical responses observed in different fertilised environments and species. As previous studies have shown declines in tree ring growth (Chojnacka-Ożga et al., 2022; Koprowski et al., 2015), we focused on finding out what changes have taken place within the annual increment that are reflected in its reduction. We hypothesised that fertilisation has a negative impact on the tree radial growth by reducing cell lumen diameter (LD) in tree-ring width (RW).

This study aims to investigate how the different concentration of N, P and K elements in post-production wastewater affects the anatomical structure of tree rings at the cellular level. We measured cell characteristics such as cell wall thickness (CWT), LD and tree-ring features such as RW, total number of cells in annual growth ring (nTotal), earlywood (EW) and latewood (LW) to investigate how these variables responded to the nutrient supply regime with added amounts of the N, P and K for the period 1984–2009. Although fertilisation took place between 1984 and 2012, the period analysed only covers the years 1984–2009. This is due to the timing limitation of the chemical data provided by Chemirol Sp. z o.o., the company that processed potatoes into starch, indicating the content of N, P and K in the post-production effluent.

Materials and methods

Site characteristics

The Forest Wastewater Treatment (FWT) commenced operation in 1984 in the Iława Forest District, located in the northern part of Poland, in the Brodnica Lake District, a few kilometres from the Iława town (Fig. 1). The FWT was designed to discharge wastewater from the potato starch factory into the forest soil. The aim was to distribute wastewater

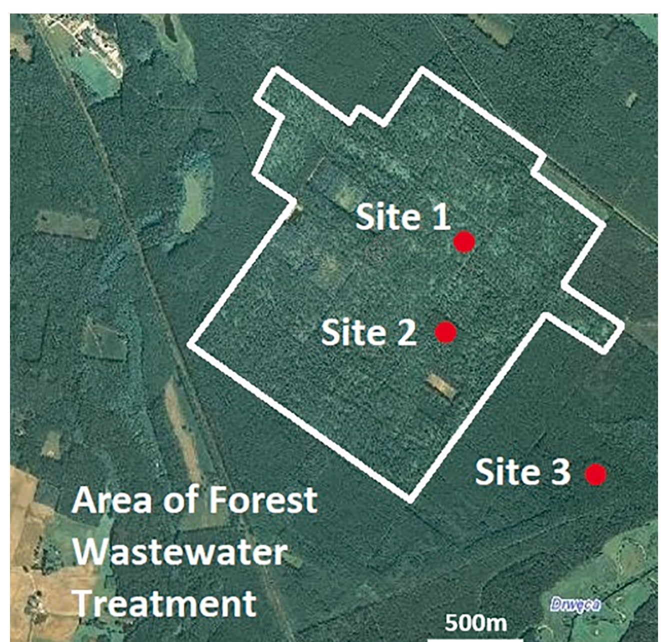

Fig. 1. Location of test sites (red circles) at the Iława Forest. Site 1: directly fertilised by wastewaters from starch factory. Site 2: not fertilised, despite being in the FWT zone. Site 3: control, not fertilised (adapted from Koprowski et al., 2015).

to purify it and contribute to the stand productivity. The facility was established at 216 hectares of pine forest growing on podzolic and rusty soils, formed on slightly loamy and loose sands with low retention capacity (Brandyk et al., 1999). The soil was the same type at each of the three sites. The mean annual air temperature and mean annual precipitation for that region are 7.6 °C and 610 mm for the period 1951–2020.

Sampling

In this study site, during the operation of the potato starch factory, the effluent was applied every 7–8 days, up to a maximum of 10 times per season. Wastewater application started after the potato harvest, which was usually in early September. The experimental forest area was 174 ha, located 7 km apart from the potato starch factory. The total length of the pipe system used for effluent application exceeded 40 km. Three sites were selected to test the effect of forest fertilisation (Fig. 1). Sites 1 and 2 were located in the FWT zone, while site 3 was a control stand located outside this zone. Site 1 and site 2 are 0.5 km apart, while site 1 and site 3 are 1.5 km apart measured in a straight line. The trees growing at site 1 were fertilised, while the trees growing at site 2 were not fertilised (Fig. 1). Although stand 2 was not fertilised, a certain amount of N, P and K must have migrated to this stand, most likely with the flow of water in the soil, as these elements were found in higher amount in the trees (Ostrowska et al., 1999). Furthermore, they were found to have a positive effect on tree growth at that site. According to the information provided by the Iława Forest District, the trees were of similar age, around 80 years in 1984. The trees showed no visible signs of disease. However, on the fertilised site 1, tree density was lower due to the snags. Using a standard 5 mm diameter Pressler borer, 120 cores were taken from pine trees growing on three sites (40 cores per site). Two core samples were taken from each tree, one from the west side and one from the east side, at a height of approximately 1.30 m above the ground.

Data treatment

The cores were prepared for measurement using standard dendrochronological procedures (Zielski and Krąpiec, 2004). Tree rings were analysed by Koprowski et al. (2015). COFECHA 6.06P (Holmes, 1983) software was used to check series intercorrelation. Each sample was analysed by means of the skeleton plot method according to (Stokes and Smiley, 1996). To analyse the effect of meteorological parameters on tree ring widths the long-term trends in tree ring widths were removed. The smoothing spline option of the dplR package (Bunn, 2008) from R (R Core Team, 2021) was used to detrend the temporal data series. The ‘‘nyear spline’’ at 2/3 the wavelength of n years was used (Cook et al., 1990). The effect of outliers was minimised using Tukey’s bi-weight robust method (Cook et al., 1990). A residual version of the chronology was built by pre-whitening after fitting an autoregressive model to the data using the Akaike information criterion (AIC) for variable selection (Bunn, 2008). At each site, the Expressed Population Signal (EPS) index was above the frequently used threshold of 0.85, indicating a high degree of common cohesion (Wigley et al., 1984). At site 1, the EPS was 0.94; at site 2, the EPS was 0.92; and at site 3, the EPS was 0.91. Analysis of site chronologies shows that before fertilisation with potato starch effluent, between 1944 and 1983, tree growth at all three sites was comparable with t-values between sites ranging from 5.8 to 7.8. For site 1 the mean of all the correlations between different cores (total rbar) was 0.52, the mean of the correlations between series from the same tree over all trees (rbar.wt) was 0.65 and the mean interseries correlation between all series from different trees (rbar.bt) was 0.52. For site 2 total rbar = 0.36, rbar.wt = 0.63, rbar.bt = 0.36. For control site 3 total rbar = 0.34, rbar.wt = 0.46, rbar.bt = 0.34.

Choosing trees for quantitative wood anatomy (QWA)

In total three trees were chosen for wood anatomical study. For each site, one tree with the best correlation with the mean chronology was chosen. A similar approach was applied by (Koprowski et al., 2018). To choose the most representative and suitable trees for QWA, the correlation of the selected sample with the master chronology (without the selected sample) was checked. For site 1 the highest correlation of the selected sample was 0.79, at site 2 = 0.74 and site 3 = 0.77 ($p < 0.05$).

Microslide preparation and wood anatomical analyses

Three selected trees were felled, and one disc was taken from each tree at breast height, 1.30 m above the ground. From each disc, a radius was selected and divided into wooden cubes of approximately $1 \times 1 \times 1$ cm. This allowed the preparation of a series of microscope slides covering all tree rings from pith to bark. Microscope slides were prepared according to the methodology proposed by (Schweingruber et al., 2006). Thin (approx. 15 µm) sections of the samples were prepared using a GSL 1 core microtome (Gärtner and Nievergelt, 2010) and then stained with safranin for cell wall staining. The sections were then mounted using a Heft Histokitt and photographed using a Canon DS126171 digital camera connected to a microscope (Olympus BX41). The microsection photographs were processed using Adobe Photoshop software (ver. 22.5.5.) to enhance the contrast between the cell wall and the lumen of the cells. In each ring (year) it was decided to select a block of five transects of cells lying directly next to each other to analyse cellular parameters. The number of cells in one transect varied from year to year and ranged from 5 to 59 cells at site 1, 29–90 cells at site 2 and 24–82 cells at site 3. Dendroanatomical calculations were performed in R (R Core Team, 2021), R version 4.2.2 (2022–10–31 ucrt) using different packages. The R package tracheideR (Campelo et al., 2016) was used to transform the raw data obtained from the image analysis into a tracheidogram to better visualise the radial intra-ring variation of the histometric parameters and to get the following parameters: CWT, LD, RW, nTotal, EW and LW (Fig. 2). Each parameter is illustrated in Figs. 4 to 9, where every point on the graph describes the average value for the entire ring. To analyse EW and LW, it was decided to use the relative percentage of earlywood (relEW) and the relative percentage of latewood (relLW), so that all annual increments can be easily compared with each other according to the method described and applied in the tracheideR package by (Campelo et al., 2016).

Periods of different fertilisation intensities

As the method of fertilisation, the water supply and the concentration of supplied elements varied over time, three 12-year periods were distinguished in which the effects of elements and selected climatic periods on the cellular parameters of the trees were analysed. The first period was before fertilisation, the so-called 'no' period (1971–1983), in which only climatic data were investigated.

The second period was, the so-called 'low' period (1984–1996), in which the utilisation of production waste and its distribution to the forest through a pipe system began. The mean amount of fertiliser applied, in the form of water solution, was 659 m^3 per year, while the mean amount of N, P and K applied was $N = 195$ mg/dm^3, $P = 32$ mg/dm^3 and $K = 318$ mg/dm^3 per year respectively.

The third period was, the so-called 'high' period (1997–2009), in which the availability of water was considerably decreased and the relative concentration of elements supplied to the environment increased. The mean amount of fertiliser applied, in the form of water solution, was 303 m^3 per year, while the mean amount of N, P and K applied was $N = 364$ mg/dm^3, $P = 43$ mg/dm^3 and $K = 521$ mg/dm^3 per year respectively. The Holm-Bonferroni method was used to test the statistical relationship between two time periods within the sites. Calculations were based on the stepAIC function and mass package

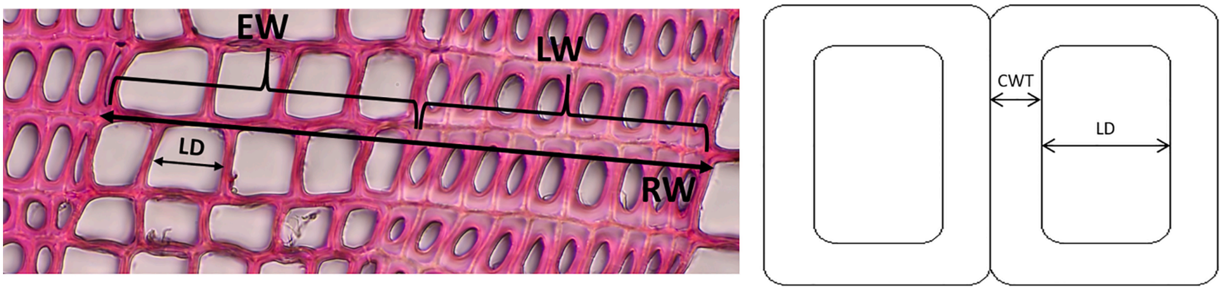

Fig. 2. Schematic representation of anatomical variables. The radial lumen diameter (LD), the cell wall thickness (CWT), ring width (RW), earlywood (EW) and latewood (LW).

(Venables and Ripley, 2002) in R. Linear regression together with AIC was used to select the best fitted model. The highest t value coefficient was chosen based on the statistically significant *p*-values > 0 and <0.05. *P*-value significance was divided as follows: 0 < *** < 0.001 < ** < 0.01 < * < 0.05. During both periods, pH was, in general constant, with a mean of 6.0, ranging from 5.5 to 6.0 in a second 'low' period (1984–1996) and 5.1–6.0 in a third 'high' period (1997–2009).

As there was no statistically significant (*p*-value < 0.05) pattern in relation between ring-widths and both daily and monthly climatic data checked for periods from 14 days to 90 days, we investigated the influence of climate from periods which are known to be important for Scots pine growing in Northern Poland (Zielski et al., 2010): the mean temperature of February and March and the sum of precipitation of May, June and July. Multiple linear regression was used to investigate the relationship between wood anatomical parameters with climatic variables, elemental concentrations (N, P and K) and wastewater volumes. The AIC was used to select the critical factors determining the width of tree rings. At first, all independent variables were used, and then a regression model with selected climatic variables and N, P and K concentrations, was applied. We used AIC to select the model that best describes the relationships between climatic factors and the effects of N, P and K on tree ring anatomy. In the first period, we only analysed the influence of climate factors, but in the second and third periods, we added analyses of the following parameters: CWT, LD, RW, nTotal, EW and LW.

Results

Two forms of data control were chosen for this experiment: (i) control site 3, located outside the FWT, where post-production wastewaters did not infiltrate (Fig. 1) and (ii) the period of tree growth before the establishment of the FWT zone (1971–1983) and the addition of wastewater.

Comparison of the sites over time

In the 'no' fertilisation period, at site 1 (1971–1983), there was a positive effect of February-March mean temperature on nTotal (Fig. 3) (specific numeric values in Table 1 in Supplementary Materials), while at site 2 May-July precipitation positively influenced total annual RW, nTotal and LD.

During the 'low' fertilisation period, at site 1 (1984–1996), a highly significant, negative effect of N (average supply 195 mg/dm^3 per year) on RW is observed, while the presence of P (average supply 32 mg/dm^3

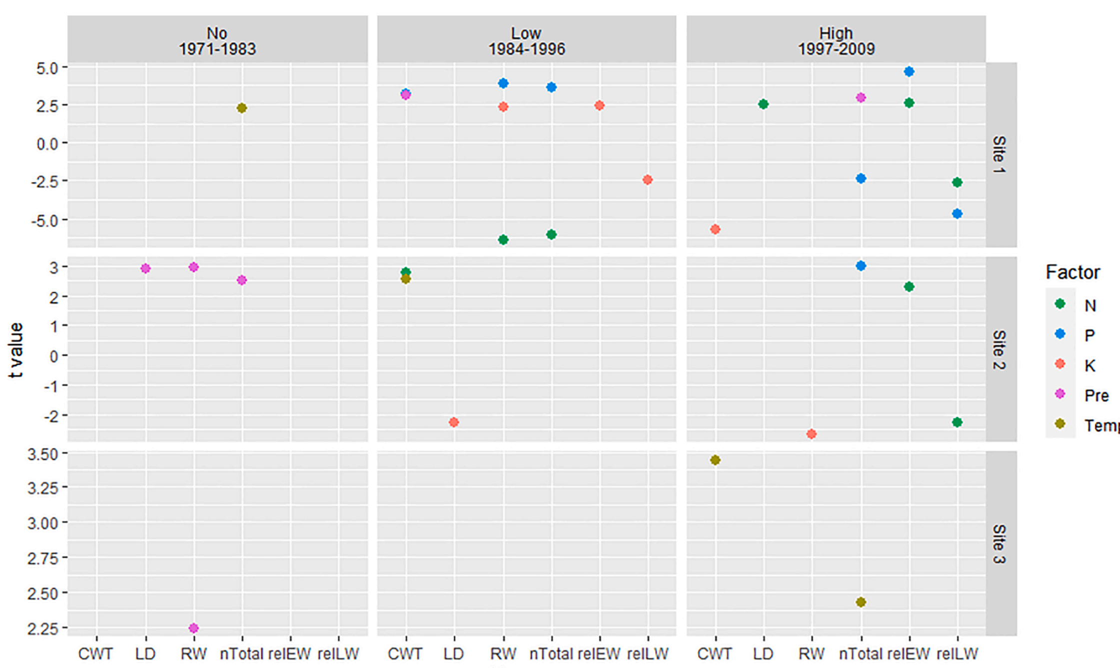

Fig. 3. Effects of N, P and K and selected climatic intervals (Pre - sum of precipitation from May to July; Temp - mean temperatures from February to March) on the cell parameters of Scots pine growing at sites 1, 2 and 3 in the Iława Forest. Dots represent the highest t values based on the statistically significant p-values: *** < 0.001, ** < 0.01 and * < 0.05. Cell Wall Thickness (CWT), Lumen Diameter (LD), Ring Width (RW), Total Number of Cells in a ring (nTotal), Relative Percentage of Earlywood (relEW) and Relative Percentage of Latewood (relLW) (Campelo et al., 2016), Nitrogen (N), Phosphorus (P) and Potassium (K) values are indicated.

per year) and K (average supply 318 mg/dm^3 per year) positively impacted RW. A similar pattern of t values coefficient is observed in nTotal. A positive effect of P was also observed for CWT. There was a positive effect of K on EW width. At the same time, at site 2, there was a negative effect of K on LD and a positive effect of N and mean February-March temperatures on CWT.

In the ‘high’ fertilisation period (1997–2009), characterised by high nutrient concentration, a significant positive effect of N (average supply 364 mg/dm^3 per year) on LD and EW width was observed on site 1 (fertilised). A particularly positive effect of P (average supply 43 mg/dm^3 per year) on EW was also noted. At the same time, the presence of P had a negative effect on nTotal and LW thickness. A strong negative effect of K (average supply 521 mg/dm^3 per year) on CWT was noted. A positive effect of May-July precipitation on RW and nTotal was observed. At the same time, site 2 recorded a negative effect of K on RW, a positive effect of N on EW width and a positive effect of P on nTotal.

At the control site, S3 (Fig. 3), during the ’no’ fertilisation period (1971–1983), annual precipitation affected only RW. During the ’high’ fertilisation period (1997–2009), average February-March temperatures significantly impacted CWT and nTotal.

A highly significant effect ($p < 0.001$) of fertiliser elements on pine cell parameters was observed at the site 1. At the same time, a lesser but significant (Fig. 3) effect of fertilisers on individual parameters, was observed at site 2 ($p < 0.05$).

Comparison of the periods within a single site

At the fertilised site 1, a statistically significant decrease ($p < 0.01$) in RW was observed between the control period "no" (before the start of fertilisation) and the period characterised by a high concentration of elements N, P and K denoted ‘high’ owing to their high supply and a drastic reduction in the water delivered to the ecosystem (data from the Chemirol Company Ltd.). In addition, a significant decrease ($p < 0.01$) of RW was also observed between the ‘low’ period, with low pollutant concentration, and the period with high pollutant concentration ‘high’ (Fig. 4).

At site 1, there was a significant decrease in CWT between the "no" and "high" periods with a $p < 0.01$, as well as between the ‘low’ and ‘high’ periods with a $p < 0.05$. A successive decrease in cell wall thickness with an increasing nutrient concentration in the wastewater was observed. In addition, at site 2, significant thickening of the CWT was observed between the control period "no" and the first fertilisation period "low" with a $p < 0.01$. At site 3, no significant change in CWT was observed over the period studied (Fig. 5).

At site 1, a significant decrease in the size of the LD was found between the ’no’ and ’low’ periods ($p < 0.05$) and between the ’no’ and ’high’ periods ($p < 0.05$). A successive decrease in the size of the LD is observed as the concentration of nutrients in the wastewater increases (Fig. 6). Although a reduction of the size of both LD and CWT is observed, it is noteworthy that the p-values are significantly smaller when tests are performed for CWT. This indicates more significant changes within the CWT.

No significant differences ($p > 0.05$) in RW and LD were observed at the unfertilised sites 2 and 3. For the nTotal parameter, no significant differences are observed within sites. The same growth pattern between RW and nTotal is observed across all sites and periods (Fig. 7). No significant differences are observed between the relEW and the relLW within sites (Figs. 8, 9 Supplementary material).

It was observed that at the fertilised site 1, the supply of nutrients delivered with wastewater resulted in a decrease of RW, CWT and LD. Only at site 2 is an increase in CWT observed due to the supply of N during the initial period of FWT functioning.

Discussion

Fertilisation alters CWT

Previous experiments with forest fertilisation have focused mainly on observing changes in stem biomass growth and have relied on measurements of tree girth or annual increments (Balster and Marshall, 2000; Hedwall et al., 2014). The novel contribution of this study is it presents the response of individual cellular characteristics to N, P and K, separating periods of different fertilisation intensities. Moreover, it describes an experiment with an extremely high supply of nutrients to the

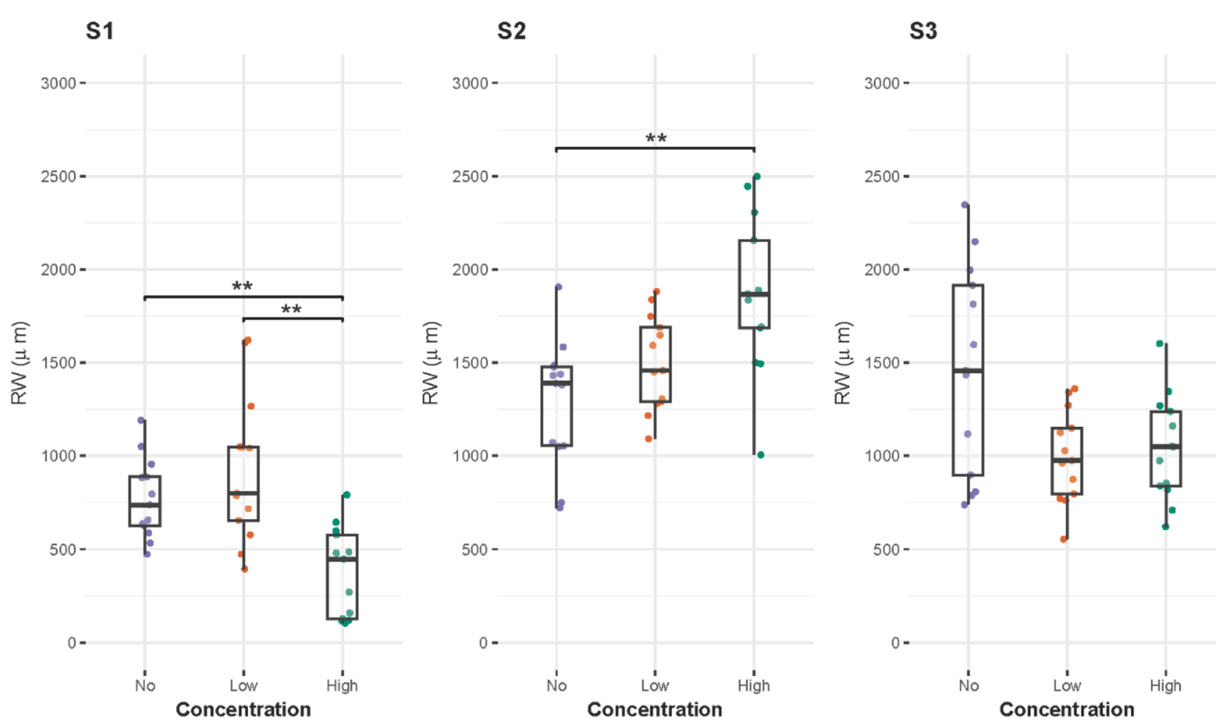

Fig. 4. Ring Width (RW) during periods with different concentrations of supplied wastewater. S1 - site 1 fertilised, S2 - site 2 unfertilised but within a zone of the Forest Wastewater Treatment (FWT), S3 - control site 3. Each point describes the average value for the entire ring.

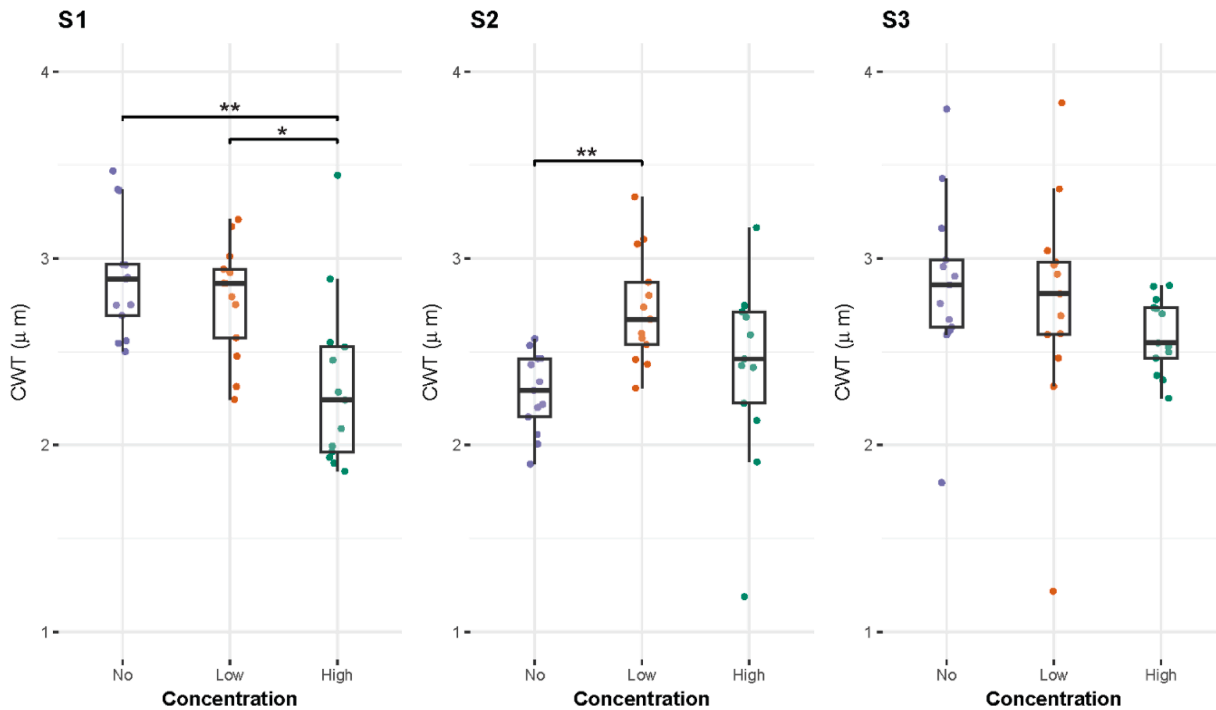

Fig. 5. Cell Wall Thickness (CWT) during periods with different concentrations of supplied wastewater. S1 - site 1 fertilised, S2 - site 2 unfertilised but within a zone of the Forest Wastewater Treatment (FWT), S3 - control site 3. Each point describes the average value for the entire ring.

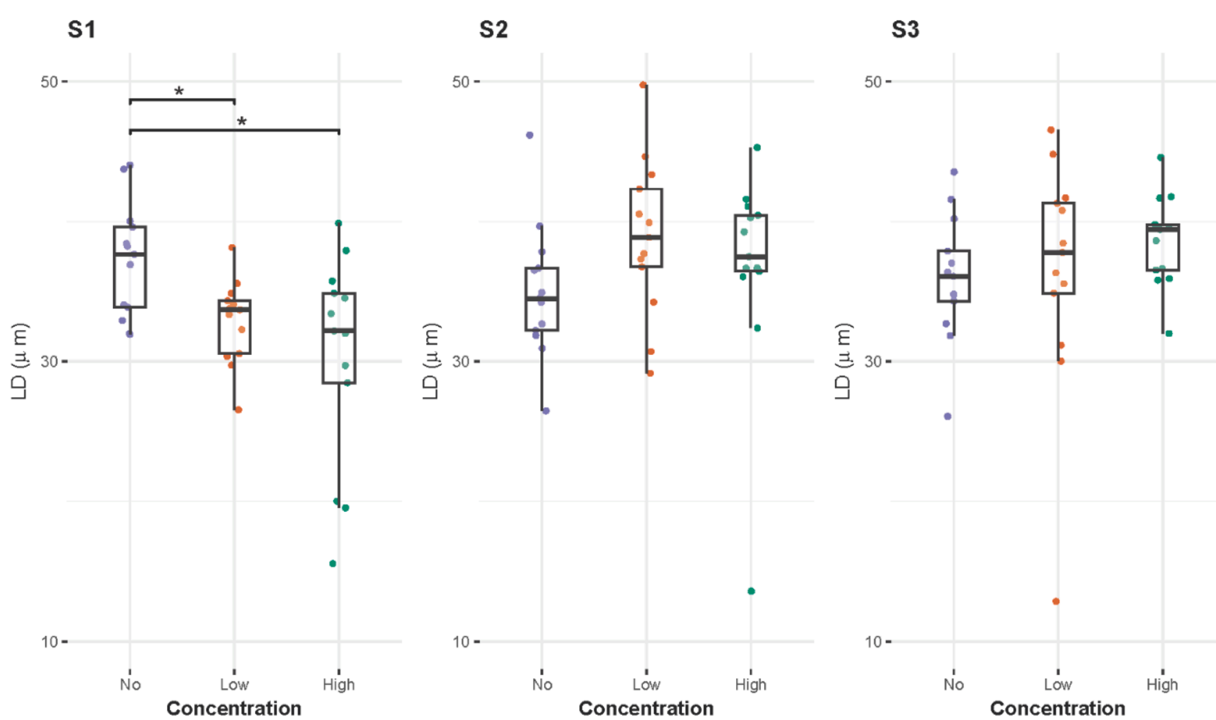

Fig. 6. Lumen diameter (LD) during periods with different concentrations of supplied wastewater. S1 - site 1 fertilised, S2 - site 2 unfertilised but within a zone of the Forest Wastewater Treatment (FWT), S3 - control site 3. Each point describes the average value for the entire ring.

ecosystem.

In this study, the main objective was to investigate how high concentrations of N, P and K in post-production wastewater affect the anatomical structure of tree rings at the cellular level. As previous studies at this site have shown a decline in tree ring growth (Chojnacka-Ożga et al., 2022; Koprowski et al., 2015), we focused on investigating the changes that have taken place within the annual increment that are reflected in its reduction. Because this study was initially established to test the hypothesis that fertilisation can have a negative impact on tree growth by reducing LD in RW, we analysed different cell characteristics such as CWT, LD, RW, nTotal, relLW and relEW to find out which factor was mostly affected by fertilisation. We observed a negative effect of fertiliser on all Scots pine cell characteristics at site 1 (fertilised), but at the same time, a lesser but significant (Fig. 3) and

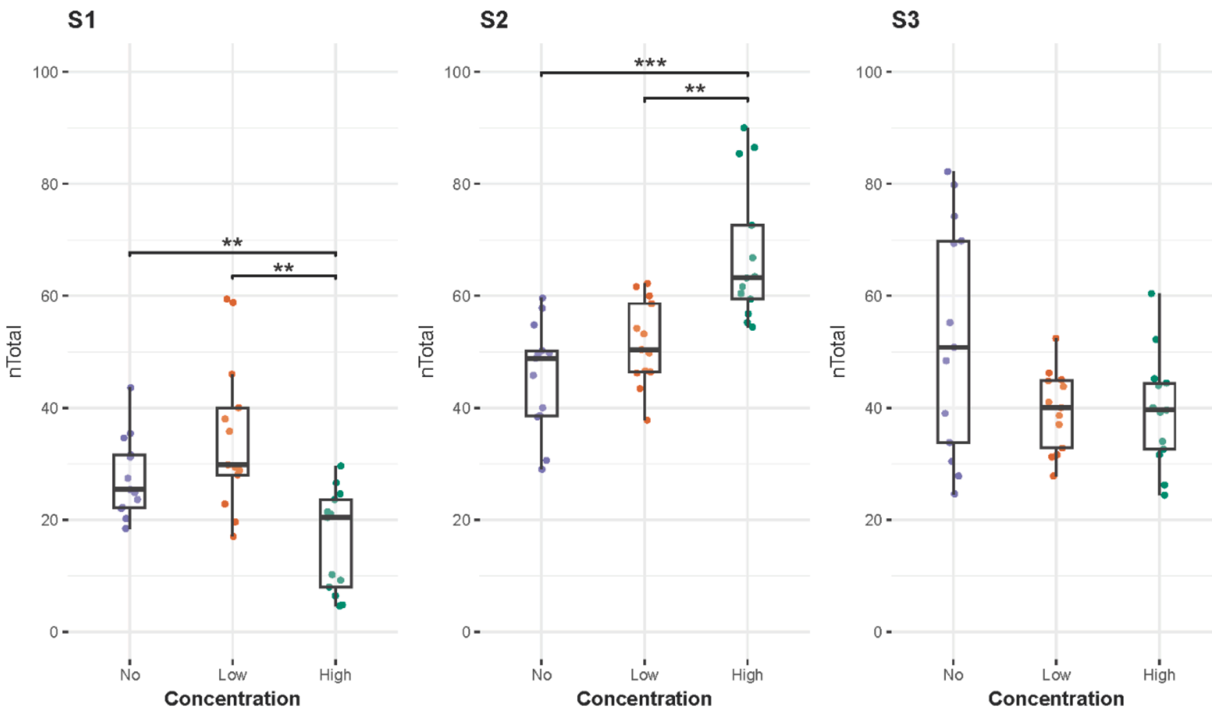

Fig. 7. Total number of cells in a ring (nTotal) during periods with different concentrations of supplied wastewater. S1 - site 1 fertilised, S2 - site 2 unfertilised but within a zone of the Forest Wastewater Treatment (FWT), S3 - control site 3.

positive (Figs. 4,5 and 6) effect of fertilisers on individual cell parameters, was observed at site 2. Technically, site 2 was not fertilised, but was located within the wastewater treatment zone. This indicates migration of contaminants within the whole FWT zone and shows the effect of fertilisation on the neighbouring plant populations, as confirmed by (Dyguś, 1999; Koprowski et al., 2015) who observed intensive growth of undergrowth forest plants. On site 2, a significant thickening of RW and an increased nTotal were observed, with a concomitant increase in CWT. At the same time, no significant changes in LD or changes in relEW or relLW were observed.

In this study, N and P are considered the most influential parameters on RW and nTotal during the first phase (1984–1996) of fertilisation (Fig. 3), while during the second phase (1997–2009) their influence switch on the CWT and relEW and relLW. At the site 1 it is observed that RW correlates well with nTotal during both 'low' (1984–1996) and 'high' (1997–2009) periods. K seems to have a negative effect on the CWT during the second phase of fertilisation (1997–2009). Although forest fertilisation experiments, where the effect of individual elements on tree growth is considered, are not rare, there are few papers where cellular parameters such as CWT, LD, nTotal together with EW and LW of maturity Scots pine forest have been analysed. In the case of EW and LW, our analysis focuses on differences between sites with different fertilisation levels and showed no statistically significant differences in the proportion of EW and LW. Recently, however, an examination of trees from exactly this location was made by (Chojnacka-Ożga et al., 2022) taking into account RW, EW and LW. They analysed the proportion of early/late wood in different periods of the FWT but divided the time into heterogeneous periods dictated by changes in the proportion of earlywood. In this approach, there was an alternating increase and decrease in the proportion of earlywood depending on fertiliser supply over 5–8 years. The difference between studies may also be due to the different time intervals adopted.

Radial growth depends on fertiliser concentration

Fertilisation is generally considered beneficial for plant growth, but as it is shown in our studies the positive effect depends on the concentration of the fertiliser. In our study, N application ranged from 176 to 1325 kg ha^{-1} depending on the year (data from the Chemirol Company Ltd.) (Koprowski et al., 2015), while published rates range from 100 to 300 kg ha^{-1} for established forests (Binkley et al., 1994). In our study, P and K were also applied in higher amounts than in other experiments. For example, in a study on the effect of fertilisation in Sweden in 1988–1989, the amount of K applied was 43 kg ha^{-1} (Kårén and Nylund, 1996), whereas in our case in 1988 about 1846 kg ha^{-1} was applied, exceeding this dose by more than 40 times. From 1999 onwards, the volume of water applied decreased while the amount of N, P and K remained unchanged, resulting in an increase in the relative concentration of these elements and consequently a decrease in radial growth. Reviews of fertiliser experiments conducted in northern countries (Denmark, Finland, Iceland, Norway and Sweden) revealed that a single application of 150 kg N ha^{-1} increases standing timber growth in mature stands of Norway spruce and Scots pine in areas with low anthropogenic N deposition (Nilsen, 2001; Nohrstedt, 2001; Óskarsson and Sigurgeirsson, 2001; Saarsalmi and Mälkönen, 2001; Vejre et al., 2001). Similar results were obtained by (Balster and Marshall, 2000) in North America where a single application of 178 kg N ha^{-1} led to a greater standing timber production in 85-year-old Douglas-fir stands in the northwestern USA and 336 kg N ha^{-1} increased tree growth in 45-year-old Ponderosa pine stands in Ontario (Groot et al., 1984). These findings were later confirmed by (Newton and Amponsah, 2006) for 21- to 100-year-old Black spruce and Jack pine stands in Canada. Most of the fertilisation studies in Scandinavia and the USA were conducted in middle-aged or older coniferous forests, which are, in terms of age, comparable to the forest we studied. According to the information provided by the Iława Forest District, the trees while sampled were of a similar age, reaching about 80 years (Koprowski et al., 2015).

Over-fertilisation might affect in physiological drought

Several studies found that over-fertilisation can lead to physiological drought, which can cause trees to die despite intensive irrigation (Ahanger et al., 2016; Ward et al., 2015). The use of excess fertilisers can be harmful to plants, depending on the type of fertiliser and time of application. Very high salt concentrations in the soil solution can reduce its osmotic potential enough to reduce water absorption, leading to leaf dehydration, closure of stomata, reduced photosynthesis, leaf damage and plasmolysis of root cells (Kozlowski et al., 1991). Previous research on this study site using RW measured from the same trees (Koprowski et al., 2015) observed that once the concentrations of N, P and K were increased in the effluent it caused a growth decrease and a weakening of the physiological condition of the trees. They concluded that the change in physiological condition can be a result of nutritional imbalance and caused osmotic stress in soil caused by the high level of nutrients itself (Elliott and White, 1994).

We found that due to the applied fertilisation regime, the Scots pine trees reduced RW, LD and CWT at site 1 (fertilised) over 12 and 24 years periods (Fig. 3). We assume that the reduction was caused by the shortages in water conductivity in plants, which might appear due to the physiological drought (Ward et al., 2015). These results confirm that the application of N, P and K at excessive rates is detrimental to forest health (Koprowski et al., 2015).

The observed wood anatomical responses are similar to those produced by drought which can be caused by the experimental conditions or occur naturally. Despite the high presence of water in the ground, due to the regular watering with water aqueous fertiliser, the amount of nutrients could cause water stress and prevent plants from taking up water from the soil. One of the indicators of normal plant development is the water content of plant tissues, which should reach 75–95 % of the mass. Using pine seedlings and soil from the FWT research zone, the water content level was determined to be 48 % of the total mass (Gumnicka, 1999). It has been reported that a too high concentration of elements in the soil solution and oxygen deficiency could cause the phenomenon of physiological drought (Ahanger et al., 2016) and lead to wilting of the seedlings. The same phenomenon may have occurred in the mature stand at the FWT zone.

We compared our results with research analysing the response of Scots pine growing under different hydrological conditions. Since the observed decrease in the size of RW, LD and CWT might be explained by the possibility of provoked osmotic stress in soil caused by the high level of nutrients itself leading to physiological drought phenomenon (Koprowski et al., 2015), we found such a comparison reasonable. (Eilmann et al., 2009) calculated the response of the same set of parameters (RW, EW, LW, CWT, LD and nTotal) to drought in Scots pine growing under relatively comparable environmental conditions and found a decrease in CWT and RW, but a slight increase in LD which is the opposite to what we observed. They also found a significant decrease in nTotal, EW and LW, which we did not observe. (Montwé et al., 2014) analysed the response of the cellular parameters of Norway spruce in an experimental drought. They observed that under drought, trees had a larger proportion of LW, smaller LD and thicker CWT, whereas in our case, no larger proportion of LW was observed, while the decrease in LD width was the same. Although we observed a decrease in CWT at the fertilised site 1, a thickening of the CWT was observed on site 2, where fertiliser might have entered the area in smaller amounts through soil water migration.

Conclusion

Despite growing on nitrogen-deficient soil, Scots pine respond negatively to frequent very high nitrogen-rich fertiliser applications. This suggests that the frequency and amount of fertiliser applied are more important for pine growth than the supply of essential nutrients. Over-fertilisation can lead to physiological drought, which can cause the trees' growth to decrease, despite intensive irrigation. While the initial fertilisation period appeared to have a positive effect on earlywood growth and cell wall thickness, the excess of nitrogen resulted in growth reduction. Our results provide a starting point for further analysis of the effects of fertilisation on tree growth, with a particular focus on its effect on individual cell parameters. Such plant physiology knowledge could be important for optimization of production of high technical quality wood.

CRediT authorship contribution statement

Nella Waszak: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Filipe Campelo:** Writing – review & editing, Software. **Iain Robertson:** Writing – review & editing, Resources. **Radosław Puchałka:** . **Fatima-Zahraa El Balghiti:** Resources, Data curation. **Jožica Gričar:** Writing – review & editing, Validation. **Ali Boularbah:** Writing – review & editing. **Marcin Koprowski:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2023.100480.

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SUPPLEMENTARY MATERIALS

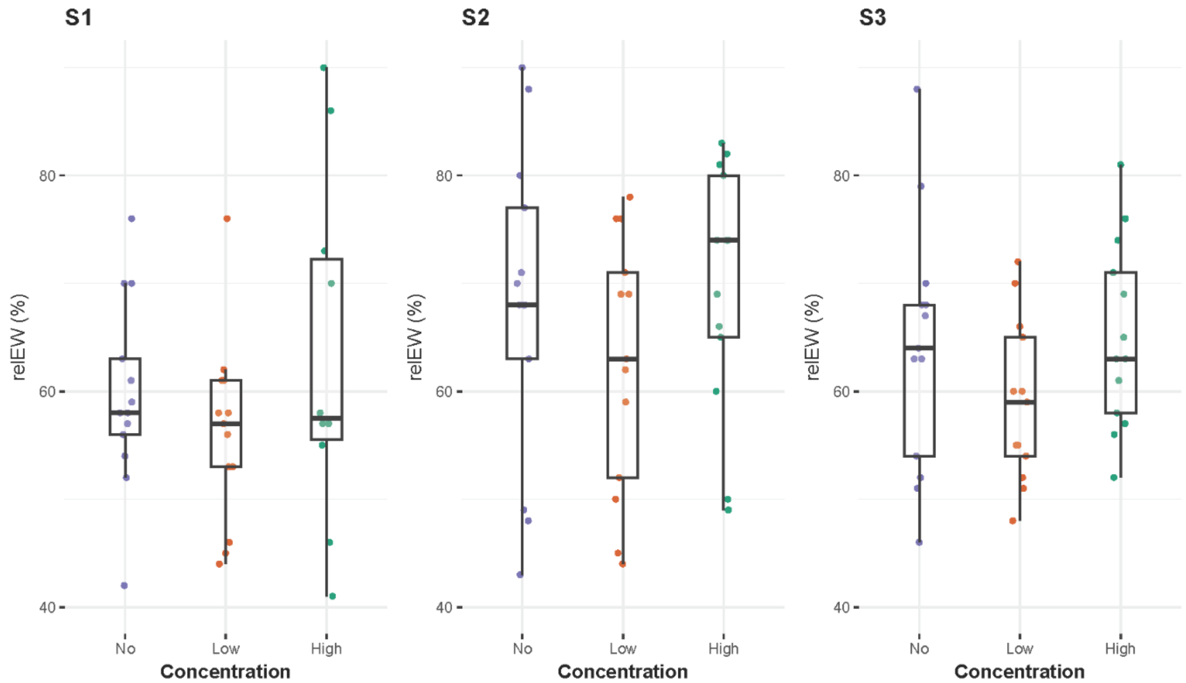

Figure 8. Relative percentage of earlywood (relEW) during periods with different concentrations of supplied wastewater. S1 - site 1 fertilised, S2 - site 2 unfertilised but within a zone of the Forest Wastewater Treatment (FWT), S3 - control site 3

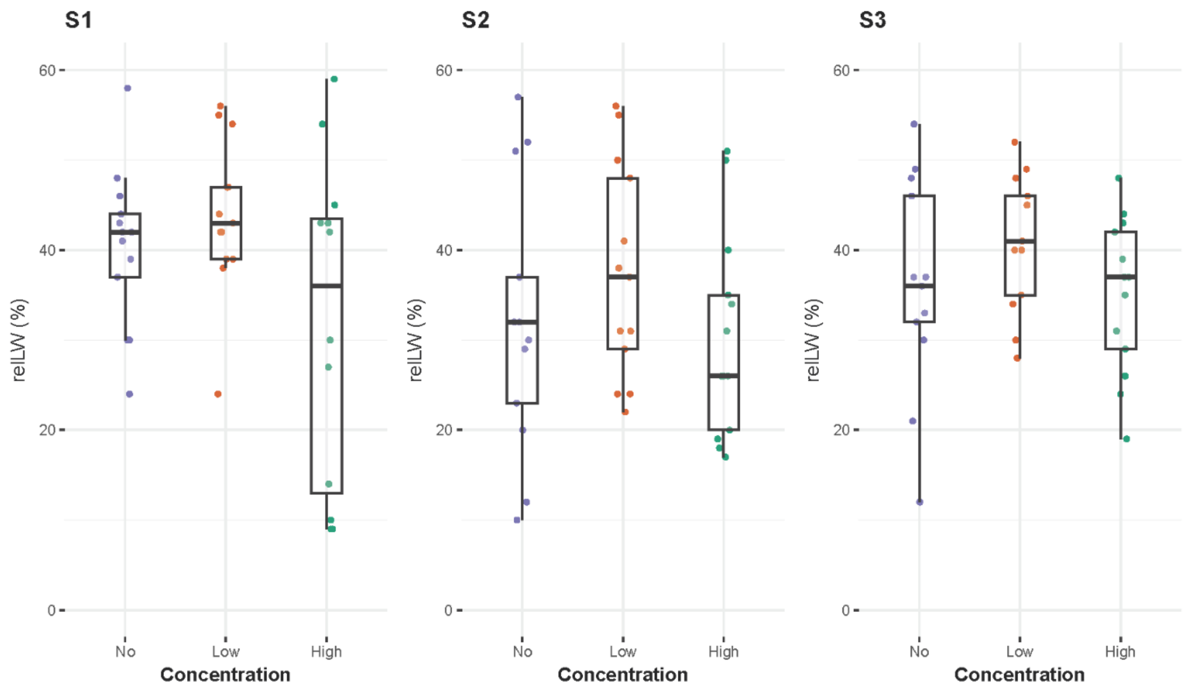

Figure 9. Relative percentage of latewood (relLW) during periods with different concentrations of supplied wastewater. S1 - site 1 fertilised, S2 - site 2 unfertilised but within a zone of the Forest Wastewater Treatment (FWT), S3 - control site 3

Table 1 Effects of N, P and K and selected climatic intervals (Pre - sum of precipitation from May to July; Temp - mean temperatures from February to March) on the cell parameters of Scots pine growing at sites 1, 2 and 3 in the Iława Forest. Numbers represent the highest t values based on the statistically significant p-values: *** < 0.001, ** < 0.01 and * < 0.05. Cell Wall Thickness (CWT), Lumen Diameter (LD), Ring Width (RW), Total Number of Cells in a ring (nTotal), Relative Percentage of Earlywood (relEW) and Relative Percentage of Latewood (relLW) (Campelo et al., 2016), Nitrogen (N), Phosphorus (P) and Potassium (K) values are indicated.

<table>
<tr><th rowspan="3"></th><th rowspan="3"></th><th colspan="3">S1</th><th colspan="3">S2</th></tr>
<tr><th>NO</th><th>LOW</th><th>HIGH</th><th>NO</th><th>LOW</th><th>HIGH</th></tr>
<tr><th>1971-1983</th><th>1984-1996</th><th>1997-2009</th><th>1971-1983</th><th>1984-1996</th><th>1997-2009</th></tr>
<tr><td rowspan="5">RW</td><td>N</td><td rowspan="3"></td><td>-6.351***</td><td rowspan="4">-</td><td rowspan="3"></td><td rowspan="5">-</td><td rowspan="2">-</td></tr>
<tr><td>P</td><td>3.835**</td></tr>
<tr><td>K</td><td>2.366*</td><td>-2.65*</td></tr>
<tr><td>mean temp. Feb-Mar</td><td rowspan="2">-</td><td rowspan="2">-</td><td>-</td><td rowspan="2">-</td></tr>
<tr><td>sum prec. May-Jul</td><td>3.107*</td><td>2.959*</td></tr>
<tr><td rowspan="5">LD</td><td>N</td><td rowspan="3"></td><td rowspan="5">-</td><td>2.456*</td><td rowspan="3"></td><td rowspan="2">-</td><td rowspan="5">-</td></tr>
<tr><td>P</td><td rowspan="4">-</td></tr>
<tr><td>K</td><td>-2.278*</td></tr>
<tr><td>mean temp. Feb-Mar</td><td rowspan="2">-</td><td>-</td><td rowspan="2">-</td></tr>
<tr><td>sum prec. May-Jul</td><td>2.91*</td></tr>
<tr><td rowspan="5">CWT</td><td>N</td><td rowspan="3"></td><td>-</td><td rowspan="2">-</td><td rowspan="3"></td><td>2.747*</td><td rowspan="5">-</td></tr>
<tr><td>P</td><td>3.156*</td><td rowspan="2">-</td></tr>
<tr><td>K</td><td rowspan="2">-</td><td>-5.72***</td></tr>
<tr><td>mean temp. Feb-Mar</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">-</td><td>2.534*</td></tr>
<tr><td>sum prec. May-Jul</td><td>3.069*</td><td>-</td></tr>
<tr><td rowspan="5">relLW</td><td>N</td><td rowspan="3"></td><td rowspan="2">-</td><td>-2.617*</td><td rowspan="3"></td><td rowspan="5">-</td><td>-2.272*</td></tr>
<tr><td>P</td><td>-4.663***</td><td rowspan="4">-</td></tr>
<tr><td>K</td><td>-2.432*</td><td rowspan="3">-</td></tr>
<tr><td>mean temp. Feb-Mar</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">-</td></tr>
<tr><td>sum prec. May-Jul</td></tr>
<tr><td rowspan="5">relEW</td><td>N</td><td rowspan="3"></td><td rowspan="2">-</td><td>2.617*</td><td rowspan="3"></td><td rowspan="5">-</td><td>2.272*</td></tr>
<tr><td>P</td><td>4.663***</td><td rowspan="4">-</td></tr>
<tr><td>K</td><td>2.432*</td><td rowspan="3">-</td></tr>
<tr><td>mean temp. Feb-Mar</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">-</td></tr>
<tr><td>sum prec. May-Jul</td></tr>
<tr><td rowspan="5">nTotal</td><td>N</td><td rowspan="3"></td><td>-6.031***</td><td>-</td><td rowspan="3"></td><td rowspan="5">-</td><td>-</td></tr>
<tr><td>P</td><td>3.592**</td><td>-2.415*</td><td>2.998*</td></tr>
<tr><td>K</td><td rowspan="3">-</td><td rowspan="2">-</td><td rowspan="3">-</td></tr>
<tr><td>mean temp. Feb-Mar</td><td>2.241*</td><td>-</td></tr>
<tr><td>sum prec. May-Jul</td><td>-</td><td>2.909*</td><td>2.493*</td></tr>
</table>

Table 1 cont. Effects of N, P and K and selected climatic intervals (Pre - sum of precipitation from May to July; Temp - mean temperatures from February to March) on the cell parameters of Scots pine growing at sites 1, 2 and 3 in the Iława Forest. Numbers represent the highest t values based on the statistically significant p-values: *** < 0.001, ** < 0.01 and * < 0.05. Cell Wall Thickness (CWT), Lumen Diameter (LD), Ring Width (RW), Total Number of Cells in a ring (nTotal), Relative Percentage of Earlywood (relEW) and Relative Percentage of Latewood (relLW) (Campelo et al., 2016), Nitrogen (N), Phosphorus (P) and Potassium (K) values are indicated.

<table>
<tr><th colspan="2" rowspan="3"></th><th colspan="3">S3</th></tr>
<tr><th>NO</th><th>LOW</th><th>HIGH</th></tr>
<tr><th>1971-1983</th><th>1984-1996</th><th>1997-2009</th></tr>
<tr><td rowspan="5">RW</td><td>N</td><td rowspan="4">-</td><td rowspan="5">-</td><td rowspan="5">-</td></tr>
<tr><td>P</td></tr>
<tr><td>K</td></tr>
<tr><td>mean temp. Feb-Mar</td></tr>
<tr><td>sum prec. May-Jul</td><td>2.242 (*)</td></tr>
<tr><td rowspan="5">LD</td><td>N</td><td rowspan="5">-</td><td rowspan="5">-</td><td rowspan="5">-</td></tr>
<tr><td>P</td></tr>
<tr><td>K</td></tr>
<tr><td>mean temp. Feb-Mar</td></tr>
<tr><td>sum prec. May-Jul</td></tr>
<tr><td rowspan="5">CWT</td><td>N</td><td rowspan="5">-</td><td rowspan="5">-</td><td rowspan="3">-</td></tr>
<tr><td>P</td></tr>
<tr><td>K</td></tr>
<tr><td>mean temp. Feb-Mar</td><td>3.441 (**)</td></tr>
<tr><td>sum prec. May-Jul</td><td>-</td></tr>
<tr><td rowspan="5">relLW</td><td>N</td><td rowspan="5">-</td><td rowspan="5">-</td><td rowspan="5">-</td></tr>
<tr><td>P</td></tr>
<tr><td>K</td></tr>
<tr><td>mean temp. Feb-Mar</td></tr>
<tr><td>sum prec. May-Jul</td></tr>
<tr><td rowspan="5">relEW</td><td>N</td><td rowspan="5">-</td><td rowspan="5">-</td><td rowspan="5">-</td></tr>
<tr><td>P</td></tr>
<tr><td>K</td></tr>
<tr><td>mean temp. Feb-Mar</td></tr>
<tr><td>sum prec. May-Jul</td></tr>
<tr><td rowspan="5">nTotal</td><td>N</td><td rowspan="5">-</td><td rowspan="5">-</td><td rowspan="3">-</td></tr>
<tr><td>P</td></tr>
<tr><td>K</td></tr>
<tr><td>mean temp. Feb-Mar</td><td>2.429 (*)</td></tr>
<tr><td>sum prec. May-Jul</td><td>-</td></tr>
</table>

Manuskrypt nr 3

Waszak, N.; Puchałka, R.; Gričar, R.; Koprowski, M. Tree rings of Scots pine (*Pinus sylvestris* L.) are more sensitive to winter temperature under the Atlantic climate but locally on precipitation.

Tree rings of Scots pine (*Pinus sylvestris* L.) are more sensitive to winter temperature under the Atlantic climate but locally on precipitation

Authors

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Abstract

This study investigates spatio-temporal analysis of climate–tree ring growth relationships in Scots pine (*Pinus sylvestris*) in northern Poland to climatic variables from 1951 to 2019. For this purpose, this time period was divided into three equal units, to compare temporal stability in growth response in oceanic and continental climates. Using 23 Scots pine chronologies from northern Poland, the study extends previous climate-growth analyses and fills spatial and temporal gaps. We found that the observed growth response of pine stands varies through the country, but forms a visual pattern. A clear distinction can be made between the influence of oceanic and continental climates in the Polish lowlands, and its line can be set along the Vistula River. Scots pines sensitivity to climatic conditions seems to change over time but also are precipitation data, which show fluctuating pattern. The thermal data, in contrast, show a steady increase in temperature, up to +1.5°C in total, with drastic increase during latest time period (1997-2019). Temperatures in winter and late spring have a dominant effect on tree-ring growth, compared to precipitation which, although less significant, can have a locally substantial effect on the radial growth of Scots pine.

Key words: dendroclimatology; coniferous forest; transitional climate; climate change

Introduction

The relationship between climate change and tree growth is complex and multifaceted, with variability in responses across species, regions, and environmental conditions. Soil properties and water availability have been identified as critical factors that can buffer or exacerbate the impact of climate change on tree growth [Lévesque i in. 2016]. Moreover, the response of tree growth to climate change is also influenced by changes in tree physiology, such as increases in intrinsic water use efficiency (iWUE) due to CO^2 enrichment, which may not fully offset the negative impacts of warming [Ren i in. 2022]. These findings underscore the need for a nuanced understanding of tree growth responses to climate change, which is essential for forest management and conservation efforts in the face of global environmental changes [Lévesque i in. 2016; Messaoud, Reid 2020; Yuan i in. 2021; Ren i in. 2022; Wang i in. 2023]. Climate change manifested by an increase in mean annual temperatures and non-linear changes in precipitation regimes are causing disruptions in previously existing climate patterns considered typical of the regions concerned. The climate disruption observed over the last century affects plant growth, especially those characterised by long growing seasons [Zunde i in. 2008; Metslaid i in. 2018; Harvey i in. 2020]. Pines growing in the temperate climate of Europe are exposed to several different types of this climate and climate change impacts conifer growth differently based on latitude. Research in Scandinavia [Reich, Oleksyn 2008] found that warming benefits conifers in northern regions but harms those in southern areas, highlighting regional variations in tree responses to temperature rise. While earlier springs and later autumns theoretically extend the growing season, increasing heat and droughts during summer may limit growth. Predictions for Poland show that by 2090, the length of the meteorological growing season is estimated to rise on average by 40–60 days in eastern Poland, while in the western part it will be longer by even 70–90 days [Graczyk, Kundzewicz 2016]. Although all tested scenarios show that an increase in the growing season will be slightly larger for western Poland than the eastern part of the country, the assumed changes are associated more with altitude than with longitude [Wertz, Wilczyński 2022]. Pollen studies show that pine (*Pinus* sp.) thrived in cooler climates, and even before recent warming, it was already outside its optimal climate niche. Further warming will exacerbate this, as shown by studies [Bombi i in. 2017; Dyderski i in. 2018]. Climate change will affect regions unevenly, and future research should focus on how wood formation responds to climatic gradients from subcontinental to suboceanic. Understanding how variables like growing season length, droughts, and heat affect growth in different regions is crucial for predicting forest ecosystem changes.

Poland lies in the temperate warm transitional climate zone, where the influences of a milder, warm oceanic climate from Western Europe clash with those of a more pronounced continental climate from Eastern Europe characterised by harsher winters. The mean air temperatures, as well as its amplitudes, differ significantly in the western and eastern parts of the country, which affects the length of the growing season, with a difference of up to 50 days [Tomczyk, Bednorz 2022]. Despite the fact that the entire area of Poland, as well as the eastern part of Germany and the western part of Eastern Europe, is considered an area of transitional climate influence, we believe that the differences resulting from the influence of oceanic and continental climate are clearly visible within the boundaries of the Polish territory. We hypothesise that there is a difference in the response of trees influenced by an oceanic climate, compared to trees influenced by a continental climate growing in a transitional climate on Polish land. In addition, the currently observed climate changes: higher air temperatures and changes in the precipitation regime, are observed in the incremental responses of coniferous trees across the country [Danek, Chuchro 2019; Waszak i in. 2021; Cedro, Nowak 2024]. We hypothesise that there is a difference in the response to temperature of trees under the influence of an oceanic climate compared to trees under the influence of a continental climate, growing in a transitional climate in Poland. The growth of trees from mild oceanic climate as less adapted to winter temperature should be more dependent on temperature variation at the end of the winter. The relationships with precipitation, as a rainfalls are a local factor, should vary and depend on local conditions. The aim is to look at the growth responses of Scots pine growing in northern Poland to climatic variables, over three equal time intervals, from 1951 to 2019 to find out whether tree rings of Scots pine species are showing responses more in line with either climate.

Harvey et al. (2020) analysed tree growth under the influence of warmer winters and summer moisture availability in northern temperate zone forests from 1943 to 2002. The pine stands they analysed in Polish areas are limited to the north-eastern Poland area only. By taking new samples and using those already collected, we decided, based on 23 Scots pine chronologies from across northern Poland, to extend the climate-growth analysis and fill this spatial and temporal gap. By doing so, we could aim to answer these questions:

(a) how did the observed temperature increase affect the climate-growth response?

(b) can a clear distinction be made between oceanic and continental climate impacts in Poland in term of climate/growth relationships ?

Material and methods

1. Study region

The northern part of Poland, where the 23 study sites, used in this study, were selected (fig.1), consists of two basic provinces: The Central European Lowland covering the western and central part of the country and the East Baltic-Belarusian Lowland covering the north-eastern part of the country [Kondracki 2002]. While the northern and southern boundaries of the Central European Lowlands are clearly defined by mountain ranges and sea coasts, its western and especially eastern boundaries have no clear delineation and are subject to debate. Within the borders of Poland, lies the south-western end of the East Baltic-Belarusian Lowland, with a surface relief similar to that of the Polish part of the Central European Lowland province.

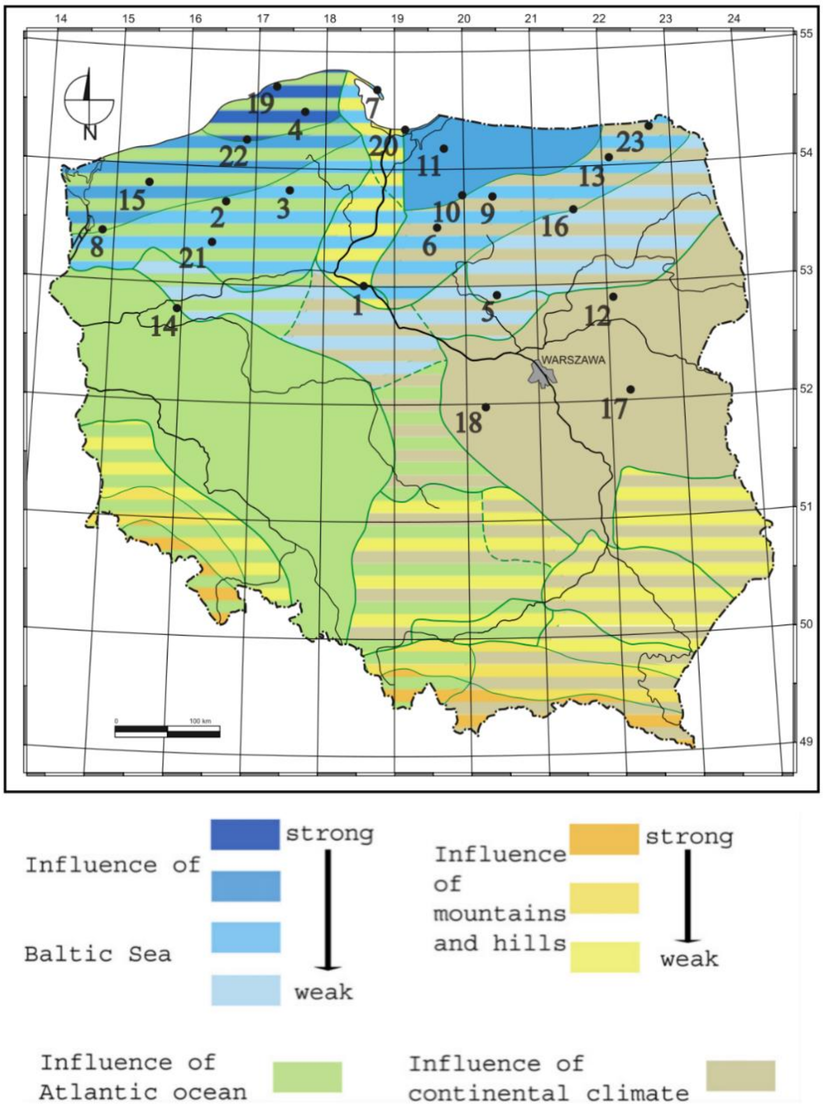

Figure 1. Localisation of research sites (dots with numbers) with climatic regions in Poland (according to Okołowicz and Martyn 1984*). Research sites: 1-Barb, 2-Bornesul, 3-borytuch, 4-Cewi, 5-Ciec, 6-ilawa, 7-jastarnia, 8-Klin, 9-kudypy, 10-Milomlyn, 11-mlynary, 12-Mysz, 13-pborec, 14-Potr, 15-Resk, 16-Ruciane, 17-Siedlce, 18-Skiern, 19-slowpn, 20-stegna, 21-walcz, 22-Warc, 23-zytkiejmy.*

The flatness of the surface of the Lowlands allows masses of marine air to move from the west far to the east. The western part of the Central European Lowlands has an oceanic climate, while the eastern part has a transitional climate between oceanic and continental. The original vegetation formation of the Central European Lowlands was forests - deciduous (beech and oak) in the west, mixed coniferous and deciduous (with pine and spruce) in the east. In the sandy areas, they gave way to pine forests and heathland. This state has been almost completely transformed as a result of long-term human activity - today primeval forests have a relict character, especially in the west of the Central European Lowlands [Kondracki 2002].

The largest percentage of the country's area is covered by Scots pine (58.8%) and oak (8%) [Biuro Urządzania Lasu i Geodezji Leśnej 2023]. The distribution of this species is not uniform across Poland, but in the northern lowland zone of Poland it is the predominant species. In the provinces where research areas were selected, pine occupies the following percentages of the total forest stand; West Pomeranian (60.4%), Pomeranian (69.5%), Kuyavian-Pomeranian (77.8%), Mazovian (71%), Warmian-Masurian (49.9%), Podlasian (57.3) [Biuro Urządzania Lasu i Geodezji Leśnej 2024]. We decided to make climate change analyses based on Scots pine because it occurs as the dominant forest-forming species in northern part of the country.

2. Tree-ring data

Chronologies collected at the Department of Dendrochronology at the Nicolaus Copernicus University in Toruń [Koprowski i in. 2012] were used, and field samples were taken from sites selected for even coverage of the area with samples [Helama, Lindholm 2003]. A total of 23 chronologies were used for analysis. At all sites, two increment cores ~1.3 m above the base of the trunk were taken from 10 to 32 trees, using a 5 mm increment borer. The 8 sites, used in the last analysed period (1997-2019), were sampled from 25 trees per site. The trees selected for sampling were healthy, with a straight trunk and a regular crown. The cores were prepared for measurement using standard dendrochronological procedures [Zielski, Krąpiec 2004]. All of the samples were air-dried, prepared with a sharp knife and scanned with 1200 dpi resolution using a standard scanner to enhance the tree ring structure. CooRecorder 9.3.1 and the related CDendro 9.3.1 software (Cybis Electronik & Data, Sweden; http://www.cybis.se) were used to measure tree-ring widths to the nearest 0.01 mm. COFECHA 6.06P software [Grissino-Mayer 2001] was used to check series intercorrelation, missing rings and detect possible dating errors. A smoothing cubic spline curve with a 50% wavelength frequency cut-off and response period of 32 years was fitted to each individual tree-ring widths series. Segments were examined in value of 50 years lagged successively by 25 years. The autoregressive model was applied to the time-series.

3. Climate data

We obtained site-specific climate data by E-OBS data set using e-obs v.28.03 version [Cornes i in. 2018]. For the analysis, daily mean temperature, daily minimum temperature, daily maximum temperature, daily precipitation sum, daily averaged relative humidity were used. As the daily minimum temperature, daily maximum temperature and daily averaged relative humidity shown no signs of statistical significance (p-value < 0.05), the entire analysis was based on daily mean temperature and daily precipitation sum with 0.1 degree regular grid. Mean temperature and sums of precipitation were calculated for each month from January to September in the growth year and May to December in the previous year. Seasonal temperature and precipitation variables were also computed by averaging monthly values (winter: December–February; spring: March–May; summer: June–Sep). Because of climate data availability, 1950-2019 time period was used, which was divided on three regular time frames: 1951-1973, 1974-1996, 1997-2019. All 23 chronologies were used in 1951-1973 and 1974-1996 time spans and 8 (never published before) chronologies were used for last 1997-2019 time period. Moreover, to check if climate data differ through time, yearly mean temperatures and yearly sum of precipitation were calculated for those time periods.

4. Tree growth responses to climate

The analyses were performed using R [R Core Team 2021] with the application of selected packages: the “dplR” [Bunn 2008] package was used to detrend the series by removing age-related growth trends and competition effects using Spline detrending method, the “treeclim” software [Zang, Biondi 2015] used a classical bootstrapped and Pearson correlation to calibrate the proxy–climate relationships together with “rcpp” and “dplr” packages. The data heatmap method was used for grouping and analysis along with a dendrogram. The Ward`s method and Euclidean distance was used for clustering. Selection of the method and number of groups taking into the consideration was used by R packages: dendextend [Galili 2015]. The “tidyheatmaps” package with heatmap() function was used to create a graphical representation of data that displays the relative intensity of values in a matrix as colours. It is used to visualise complex data sets and identify patterns, correlations and outliners. In this study, used to present correlation between study sites and monthly meteorological parameters, for months and seasons. Function also allows to display a dendrogram that was used to group sites into those under influence of Atlantic Ocean climate and continental climate.

Results

Changes in temperature and precipitation 1951-2019

To check if climate data differ through time, yearly mean temperatures and yearly sum of precipitation were calculated for three time periods chosen. In case of temperatures, at all study locations, temperature rise was observed and the change was up to +1.5°C in total (fig. 2). Comparing the change between the first period (1951-1973) and the second (1974-1996), the change was often about 0.2~0.3°C. Nonetheless it was observed that temperatures increased dramatically in the third period (1997-2019) up to about 1°C, compared to the second period (1974-1996).

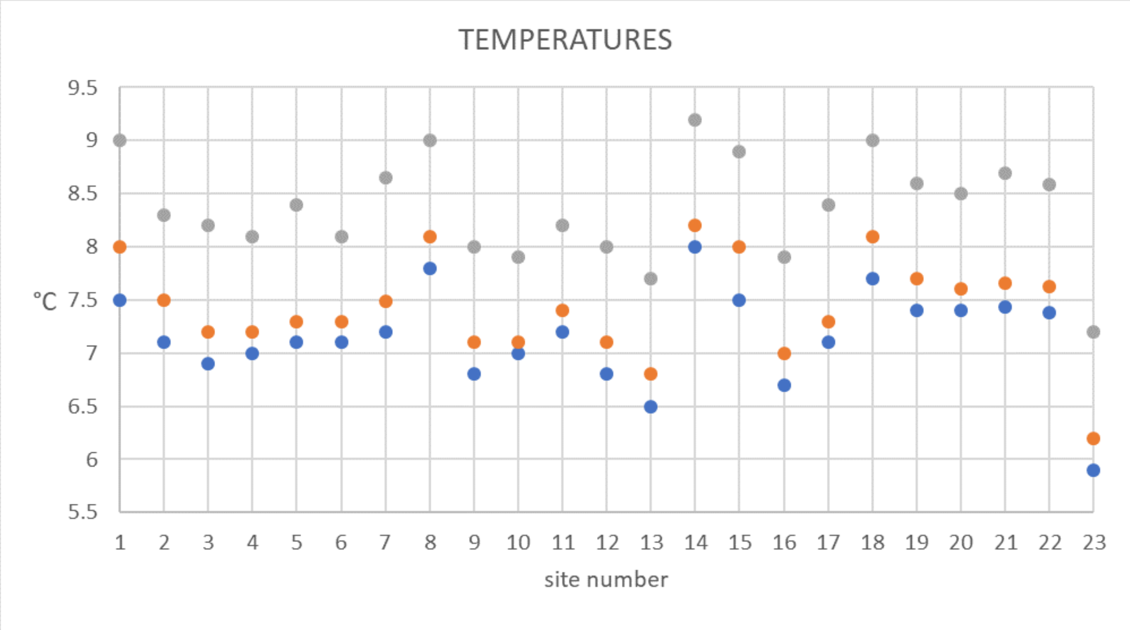

Figure 2. Mean temperatures for three time periods analysed at each research site. Research sites: 1-barb, 2-bornesul, 3-borytuch, 4-cewi, 5-ciec, 6-ilawa, 7-jastarnia, 8-Klin, 9-kudypy, 10-milomlyn, 11-mlynary, 12-mysz, 13-pborec, 14-potr, 15-resk, 16-ruciane, 17-siedlce, 18-skiern, 19-slowpn, 20-stegna, 21-walcz, 22-warc, 23-zytkiejmy.

Despite this, in case of precipitation the observation is not linear and we haven't observed any spatial pattern for it. Some study sites showed a progressive decrease in rainfall, as for example sites 1, 5 or 15 (fig. 3). Some showed a progressive increase in rainfall, for example sites 14, 22 or 23 (fig. 3). Nevertheless, some of sites showed decreased sum of precipitation in second time period (1974-1996) comparing to the first one (1951-1973) and then in the third time period (1997-2019) higher sums of precipitation, higher even comparing to the first time period, for example sites 2, 3 or 18. For precipitation totals and average temperatures for the time periods analysed, see supplementary material tab. 1.

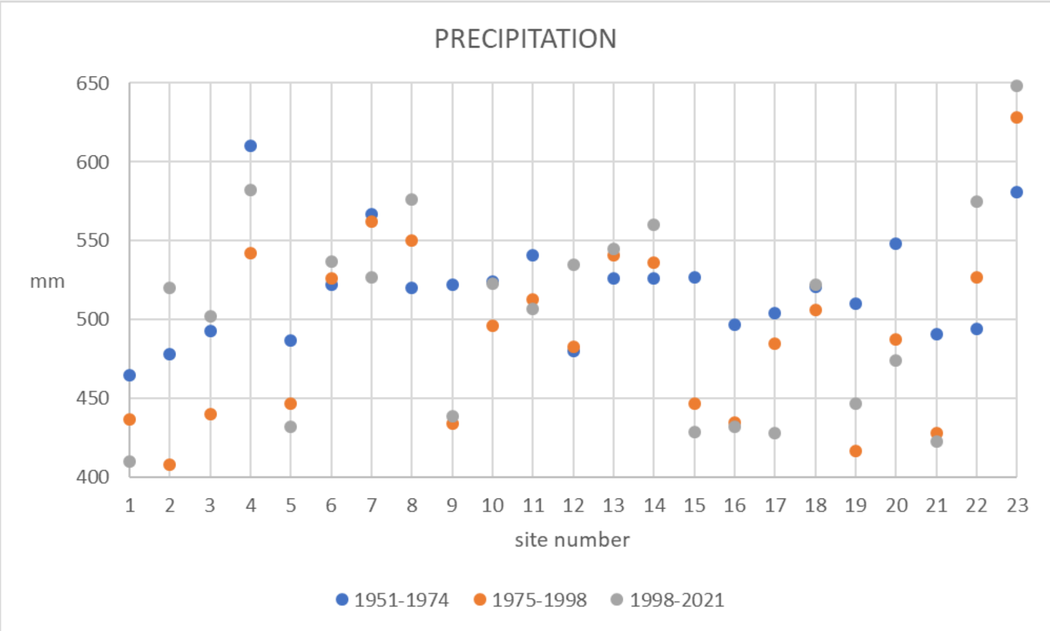

Figure 3. Mean sums of precipitation for three time periods analysed at each research site. Research sites: 1-Barb, 2-Bornesul, 3-borytuch, 4-Cewi, 5-Ciec, 6-ilawa, 7-jastarnia, 8-Klin, 9-kudypy, 10-Milomlyn, 11-mlynary, 12-Mysz, 13-pborec, 14-Potr, 15-Resk, 16-Ruciane, 17-Siedlce, 18-Skiern, 19-slowpn, 20-stegna, 21-walcz, 22-Warc, 23-zytkiejmy.

To find out whether a clear distinction can be made between the influence of oceanic and continental climates in Poland, for each time period, we have created a heatmap presenting site correlation between tree rings width and monthly and seasonal climate data. Analyse goes together with dendrogram that groups sites within being under the influence of the continental climate and the influence of the Atlantic Ocean climate.

1951-1973 first time period: heatmap

At most sites, the highest correlation of tree-ring widths was observed for winter and spring temperatures (fig. 4). Especially high correlation between tree-ring widths of Scots pine and temperatures was detected in February and March and in some cases also in April. Slight correlation was observed for temperatures of previous year December, but mostly non for January. Sites located in western part of Poland: Bornesul, Klin and Potr, does not share common, for the other sites, pattern and show no response to months and season temperatures aforementioned, but show a similar response to each other and are grouped together by the dendrogram function.

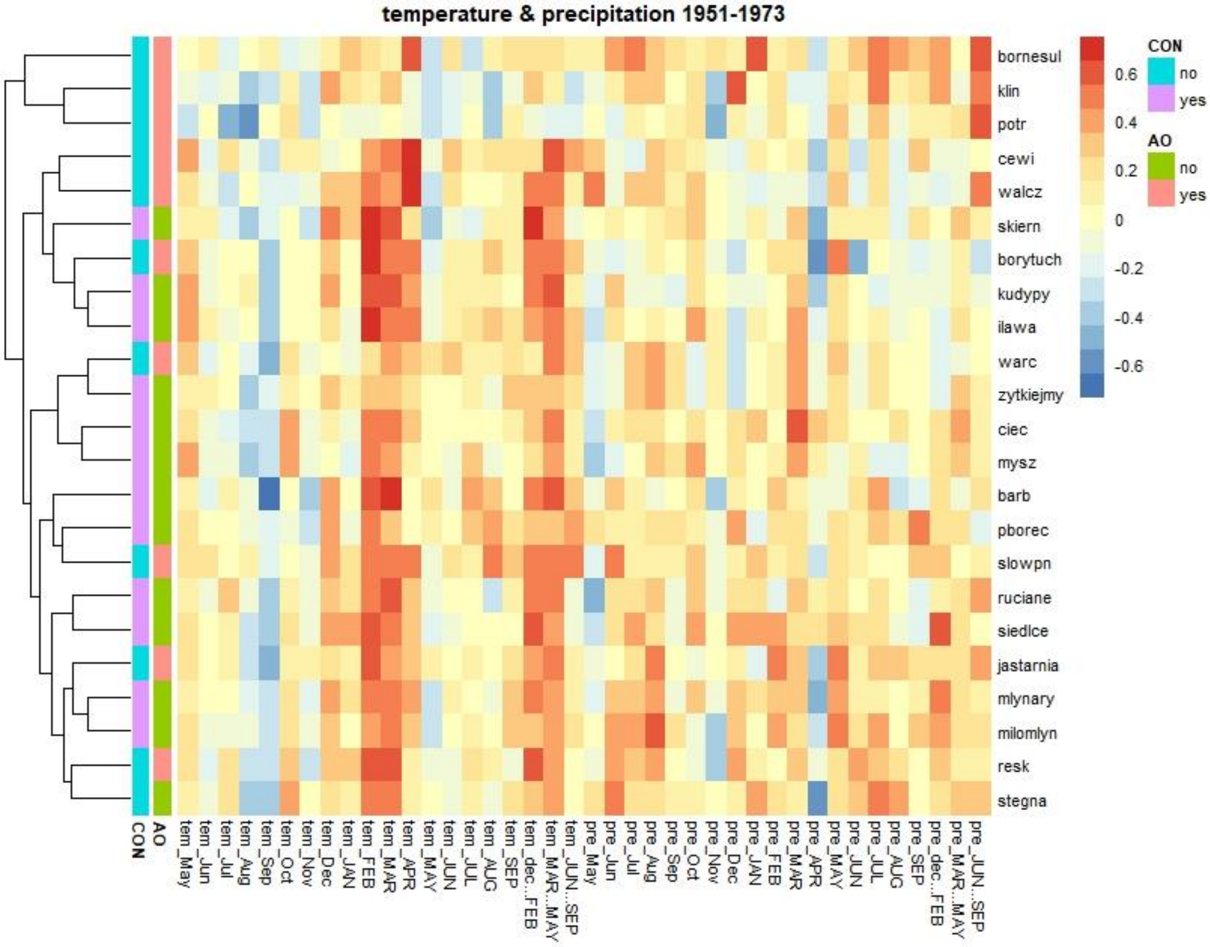

Figure 4. Heatmap of temperature and precipitation correlations with research sites for 1951-1973 time period, for all months from May previous year to September of current yearanalysed and for seasons: winter (dec…FEB), spring (MAR…MAY), summer (JUN…SEP). AO-Influence of Atlantic Ocean climate, CON-Influence of continental climate.

Precipitation do not show any spatial and temporal pattern. Only an exceptionally high correlation with precipitation is evident for the Klin (January) and Bornesul (February) locations. Those sites, together with Potr site are also the only one highly reacting at summer precipitation. For numeric values of correlation for temperatures check tab. 2 file and for precipitation data tab. 3 file in in supplementary material. There is also no clear separation between the influence of continental climate and that of the Atlantic Ocean in the dendrogram analysis.

1974-1996 second time period: heatmap

In general, comparing to the first time interval, we found a decrease in the response of tree-ring width of Scots to winter and early spring temperatures at all study sites (fig. 5). In particular, the decrease was most evident at western sites; i.e. Potr, Resk, Cewi and Klin, but not only, it also appeared at Skiern, Milomlyn sites. Also, all mentioned sites do not show pattern in precipitation correlation. All other 18 sites in western, central and eastern Poland show a similar response to mean monthly temperatures, with a strong correlation to January, February, March and April. In addition, the strongest Pearson correlation values, above 0.7, are observed during the winter season. Some sites show moderate correlation with temperature, above 0.4, during spring season. A negative correlation between tree-ring widths and temperatures values is also more frequently observed, but in most cases it is not significant.

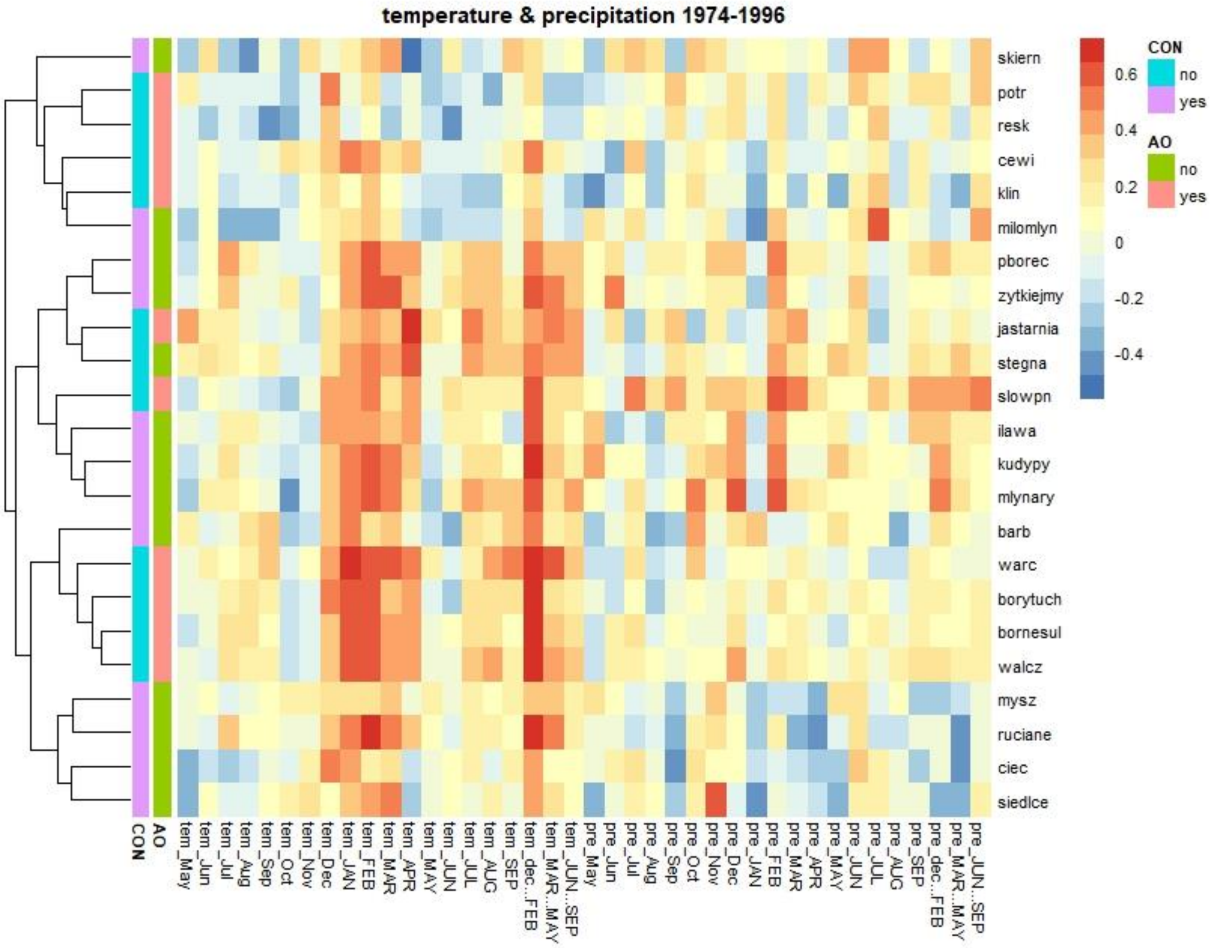

Figure 5. Heatmap of temperature and precipitation correlations with research sites for 1974-1996 time period, for all months from May previous year to September of current yearanalysed and for seasons: winter (dec…FEB), spring (MAR…MAY), summer (JUN…SEP). AO-Influence of Atlantic Ocean climate, CON-Influence of continental climate.

For precipitation, there is not such a strong pattern, but two groups with moderate values can be distinguished (with p-values around 0.3-0.5). The first, with a positive correlation of precipitation values in February, but without spatial correlation. The second, with sites located in eastern Poland (Mysz, Ruciane, Ciec, Siedlce) with a negative correlation of precipitation from January to May of the current year and September of the previous year. In this group, the same strength of correlation is observed in the spring season. These sites have also been categorised by dendrogram function, as being under the Atlantic Ocean climate influence.

1997-2019 third time period: heatmap

The northern Poland sites show a clear division of the influence of continental and oceanic climate. The eastern site (Mysz) and sites form central Poland (Barb, Ciec) are categorised, as being under continental climate influence (fig. 6). The rest of the sites from western Poland are grouped by the influence of oceanic climate. At all sites there is moderate to strong influence of March temperatures on tree-ring widths. Moreover, sites from western part of the country, show moderate influence of February temperatures. In addition, the sites located near the Baltic Sea area (Cewi, Warc, Resk) show positive, significant influence of winter and spring temperatures on tree-ring widths, but they do not show any characteristic pattern in precipitation correlations. All analysed sites show negative correlation with July temperatures and most sites show significant negative correlation with summer season temperatures. More positive response of winter temperatures on tree-ring widths is visible at sites under influence of oceanic climate (Cewi, Warc). For sites under the influence of continental climate stronger negative response to temperatures in late spring (May) and summer months (June-September) was

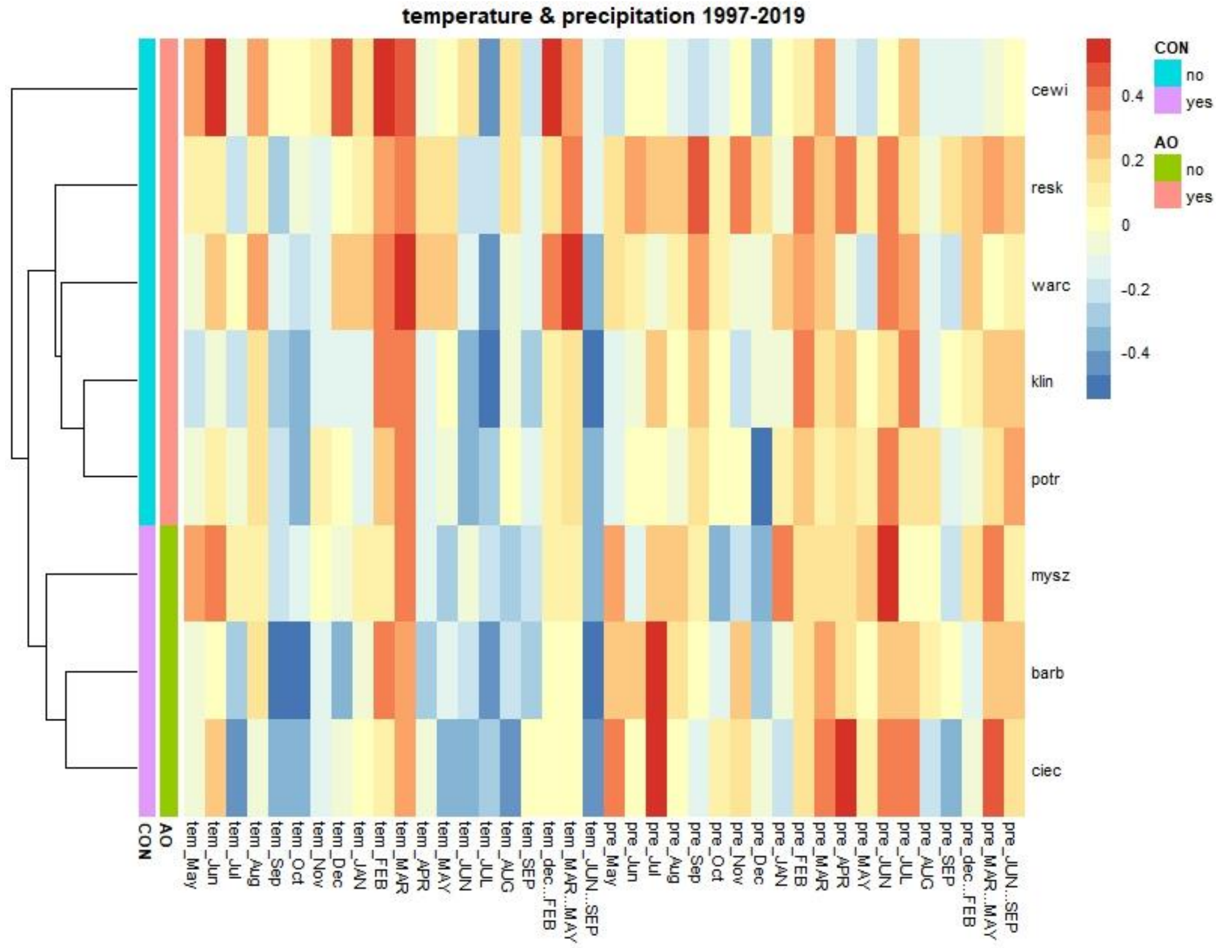

Figure 6. Heatmap of temperature and precipitation correlations with research sites for 1997-2019 time period, for all months from May previous year to September of current yearanalysed and for seasons: winter (dec…FEB), spring (MAR…MAY), summer (JUN…SEP). AO-Influence of Atlantic Ocean climate, CON-Influence of continental climate.

observed. There is no strong pattern in the case of precipitation; however, strong, positive influence of July precipitation on tree-ring width is observed at central Poland region at Barb and Ciec.

Discussion

Yearly mean temperatures and yearly sum of precipitation for three time periods were calculated. A significant increase in temperatures was found, up to +1.5°C in total. Though, the third period (1997-2019) saw a dramatic increase, up to 1°C (fig. 2). For precipitation the trend is not linear and no spatial pattern have been observed, also data very rarely gave a significant result (fig. 3), similarly to [Juknys i in. 2002; Augustaitis i in. 2015; Läänelaid, Helama 2020]. As temperatures increased consistently in all locations and precipitation showed no significant data, it can be assumed that temperatures are the main shaping growth factor in this region of Europe. This is consistent with the growth projections for Scots pine [Lasch i in. 2002], in the model where steadily increasing temperatures, together with higher precipitation, give a positive growth correlation, while decreasing precipitation, with increasing temperatures, showed negative growth correlations.

In the first time period (fig. 4) at most sites, the highest correlation of tree-ring widths of Scots pine was observed for winter and spring temperatures, especially for February and March. Only 3 sites out of 23, located in the western part of the country, have not shown that correlation, being under influence of the oceanic climate and in general higher temperatures. In the second time period (fig. 5), subsequently, a smaller number of sites (17 out of 23), but still by far the most prevalent, showed the highest correlation with the temperatures in late winter and early spring. The sites where tree-ring widths of Scots pine did not react positively to temperatures at the end of winter and the beginning of spring are located in the western part of Poland and in the Baltic Sea influence belt. The differences in response are due to the reactions to locally changing rainfall total sums.

In the third time period (fig. 6), a clear division of sites into zones of influence of oceanic and continental climates is marked. There is a weaker response to winter temperatures than before, also recently observed by [Metslaid i in. 2018]. All sites showed a significant response to March temperatures, while sites influenced by the oceanic climate also showed a significant influence of February temperatures. At the same time, sites along the Baltic Sea coast showed a significant reaction to temperatures of both the winter and spring seasons. On the contrary to the previous time periods analysed, all sites showed negative influence of July temperatures on the radial growth of Scots pine, while sites influenced by continental climate, also showed a significant negative influence of temperatures from May to September. We interpret, that negative reaction to the summer temperatures goes together with positive response to summer precipitation, as the continental climate is characterised by higher sums of precipitation in summer [Misi i in. 2019]. During that third time period, when mean temperatures rose about 1.5°C, compering to the first time period (1951-1973), we indicate strong negative influence of temperatures and positive influence of precipitation on the radial growth of Scots pine.

Atlantic Ocean climate Influence

In line with the hypothesis that the differences in the response of Scots pine radial growth are due to divergence in oceanic and continental climates, the spatial distribution of sites in the thermal impact analysis speaks in favour. Although, the response along sites is generally mixed, it is very pronounced in the western sites: Potr, Klin and Resk, located along the German border, characterised by the highest air temperatures and similar to each other annual amount of precipitation. These sites stand out from the rest of Poland over the entire time period analysed (fig. 4, 5, 6). They showed no reaction to February and March temperature during first and second time period and strong reaction to these months in the third time period, inversely to the rest of the sites. Those three western sites show some similarities in radial growth of Scots pine to German's stands. In line with the findings [Von Lührte 1991; Bauwe i in. 2013], Bauwe (et al. 2015) found a moderate effect of winter temperatures on pine radial growth in western and central forests of Germany. The growth-promoting effect of warmer winters in climate projections therefore seems to balance the negative impact of increasing summer drought, especially in June. [Diers i in. 2024] found out that increasing winter temperatures stimulate scots pine growth in the north German lowlands despite stationary sensitivity to summer drought. Furthermore, [Ellenberg, Christoph 2010] confirms that in the temperate lowland forests of north-eastern Germany, Scots pine experiences optimal growth conditions in a physiological sense. The considerably similar tree response in the third, warmest period, of sites from western Poland, both those along the border with Germany (Potr, Klin and Resk) and those along the Baltic Sea line (Warc and Cewi), which are additionally under the influence of a milder marine climate that indicates a significant influence of warm air masses of the Atlantic Ocean climate.

Continental climate influence

In the temperate climate of Central and Eastern Europe, it is widely observed that winter and early spring temperatures, as well as summer droughts, have a significant impact on pine radial growth. Our sites from central and eastern Poland show climate-growth responses similar to the others from Poland [Koprowski i in. 2012; Waszak i in. 2021], Estonia [Vitas 2006; Metslaid i in. 2018; Läänelaid, Helama 2020] or Lithuania [Juknys i in. 2002; Augustaitis, Bytnerowicz 2008; Augustaitis i in. 2015]. February temperatures are considered to be particularly important for pine growth, however, the growth responses of pine trees are not always uniform and can vary from individual to individual indicating also, to a lesser extent, the importance of January and March [Vitas 2006]. Although pine is a species adapted to low winter temperatures, it has been observed that warmer end of winter/early spring period promotes Scots pine growth during the following growing season [Juknys i in. 2002; Augustaitis i in. 2015; Läänelaid, Helama 2020; Waszak i in. 2021]. In our analysis, when comparing the three time periods between which there was a constant increase in temperature at all sites, the opposite trend was observed. The warmer the winter, the smaller the response to late winter/early spring temperatures (figs. 5, 6). We suspect that higher temperatures (fig. 2), combined with locally occurring decreases in rainfall totals (fig. 3), may lead to water stress [Edwards, Dixon 1995; Lasch i in. 2002].

Not only in Poland, Scots pine trees are sensitive to winter cold and have statistically significant positive correlations with February and March temperatures [Opała, Mendecki 2013]. In Estonia, the most stable links between the radial growth of pines and temperature are found in March [Vitas 2006]. A high correlation of February and March temperatures with pine growth was also observed by Läänelaid and Helama (2020) who, similarly to our study, noted a lack of sensitivity to precipitation. Also in Lithuania, faster growth of pine trees was recorded in correlation with higher winter season temperatures, while precipitation was identified as insignificant [Augustaitis i in. 2015]. Our results appear to be in agreement with the above study, where a steady increase in temperatures over the years was observed, but also because the fact that, in western sites of Lithuania, pine growth is limited by cold temperatures from December to April, as a result of plants dormancy period [Augustaitis i in. 2015]. In our study, we observe similar reaction during second time period (1974-1996). In Latvian latitudes, temperatures of late winter in February and early spring in March and April affect the pine growth rate most strongly [Juknys i in. 2002]. In that study, precipitation was also less significant, as the temperature was the most influential factor determining radial growth of Scots pine. Temperatures of February, March and beginning of April show positive correlation with Scots pine growth in Fennoscandia, Latvia, Poland and Germany [Zunde i in. 2008; Wilczyński 2013], but reaction to summer temperatures are not that commonly shared. In our study, positive June precipitation appeared, at the end of the timeline (fig. 6) in 1997-2019 time period. Positive growth reaction to June precipitation was observed in Poland in dendrochronological studies of 1861-2000 chronology [Koprowski i in. 2012] but also in Southern Finland [Helama i in. 2012] for June and July. In Estonia [Metslaid i in. 2018] observed significant positive correlations with winter/early spring temperatures and, in the contrary to our results, positive correlations to total precipitation of late summer in the year prior to growth. Moreover, they observed that associations between Scots pine tree-ring width and winter temperatures are getting weaker. Our study indicates similar observation where importance of February is weakened, while March gets more prominent during third analysed time period (1997-2019). The shift in importance from February to March may be linked to changes in the growing season and climate. [Waszak i in. 2021] found March's precipitation and temperature had the strongest impact on tree rings in northern Poland, suggesting March's increasing relevance due to climate change. This contrasts with Koprowski i in. [2010], who found February-March temperature a stable factor for pine growth. This highlights the evolving nature of climate-growth links and the need for up-to-date data. Continuous monitoring is essential to understand how environmental changes affect tree growth.

The physiological effects of contrasting climatic conditions are complex and not fully understood. The strong association with winter and early spring temperatures suggests that wider Scots pine tree rings are formed in years with warm winters and springs. Nevertheless, in our study, this observation is accurate for the years 1951-1973 and decreases over time to, surprisingly, be seen mainly in the western, warmer areas. However, the strong association with winter/early spring temperatures is consistent with previous studies in the Baltic Sea region [Stravinskienė 2000; Läänelaid, Eckstein 2003; Vitas 2008; Maris Hordo i in. 2009; M. Hordo i in. 2011; Koprowski 2012; Bauwe i in. 2013; Helama i in. 2014]. Several physiological explanations for this association can be proposed, including frost damage to fine roots during very cold winters, especially when the snow cover is not thick and does not provide root protection [Hardy i in. 2001; Tuovinen i in. 2005]. [Sperry i in. 1994] hypothesise that winter cold causes xylem blockages, which disrupts stem water conductivity. Harsh winters can cause defoliation of conifers the following spring [Kullman 1991] leading to lower stem biomass production due to reduced photosynthetic capacity [Ericsson i in. 1980]. According to [Ensminger i in. 2004], the most stressful periods for pine forests in boreal climates, and therefore significantly influenced by the continental climate, are winters and early springs, when low temperatures limit photosynthesis. They found that the production of chlorophyll-regulating pigments and the progress of photosynthetic regeneration are closely linked to thermal conditions in spring, and that temporary periods of low temperatures during this period can even have the opposite effect on physiological regeneration. Moreover, the delayed melting of snow and thawing of the soil after very cold winters may limit the uptake and flow of water and nutrients in trees and delay the initiation of cambium activity [Vaganov i in. 1999], which may be the case in the eastern Poland, where winters are more severe. Therefore, warm springs also favour the restoration of transport capacity in the xylem and phloem [Vanhatalo i in. 2015]. Koprowski i in. [2012] established a centuries-old Scots pine chronology from central Poland and compared it with chronologies from Lithuania, Estonia and Germany, indicating that it is more similar to German chronologies. Analysing contemporary chronologies from the area of the whole of northern Poland, we observe a division of the response of sites from the western part of the country into those similar to German stands, and those from central and eastern Poland similar in response to those from Lithuania or Estonia. This indicates a shifting of the dividing line of the influence of oceanic and continental climates to the west.

Variability of tree responses over time

Relationships between tree-ring widths and climatic factors are inconsistent over time and sometimes space, e.g. the Bornesul or Milomlyn stands, and vary from period to period, indicating some instability in the response of Scots pine to climatic conditions over relatively short periods of time. [Wilczyński 2013] indicates that in stands located in the Białowieża Forest in north-eastern Poland, under homogeneous climatic conditions, Scots pine on 14 different sites showed a similar short-term incremental rhythm, which was determined by early spring temperature and rainfall in June. Nevertheless, the differences in growth pattern were due to the different sensitivity of pines from various habitats, indicating soil as an important environmental factor. In our study, in the first (1951-1973) and the second (1974-1996) time periods, the chronologies used in the analysis consisted of samples from different parts of Poland which were taken at different times with the assumption that they would be used in multiple types of analysis (15 chronologies) and samples taken specifically for this study in year 2022 (8 chronologies). The chronologies used in the analysis of the third period (1997-2019) were selected using a homogeneous methodology, from similar habitats and from trees of approximate age. This may explain this clear division of sites in the third time period (1997-2019) into those influenced by oceanic and continental climates (fig. 6), and less evident division in earlier periods, when the signal is disturbed. Studies carried out on several lowland sites in Western Poland, between 50 km and 150 km apart, show that even at short distances from each other, the trees' responses to climatic conditions can vary [Cedro 2001]. This shows that pine trees can respond differently according to the precipitation totals, distribution of precipitation and, although precipitation has a lower effect on growth than temperatures, it is a locally important factor in differentiating the incremental responses of Scots pine trees. Analysing the distribution of the variability of precipitation totals over time (fig. 3), it is possible to observe their local character, making it difficult to interpret the results unambiguously in the transitional climate zone. [Vitas 2006] also proved that trees, depending on their distribution in the forest, can show significant responses for different months, so that the variable responses between sites can somehow be explained by the individuality of tree responses.

Conclusion

On the basis of current data, a clear distinction can be made between the influence of oceanic and continental climates in the Polish lowlands, and its line can be set along the Vistula River. The response of Scots pine stands is not the same throughout northern Poland and varies from location to location, but forms a visual pattern depending on the influence of the climates. Temperatures in winter and late spring have a dominant effect on tree-ring growth, compared to precipitation which, although less significant, can have a locally substantial effect on the radial growth response of trees. As climatic variables have been changing rapidly over the past century, changes in the radial growth of Scots pine are becoming unstable.

Anknowlegments

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SUPPLEMENTARY MATERIALS

Tab. 1 Precipitation totals and average temperatures for the time periods analysed

		temp mean			pre sum		
		1951-1974	1975-1998	1998-2021	1951-1974	1975-1998	1998-2021
1	barb	7.5	8	9	465	437	410
2	bornesul	7.1	7.5	8.3	478	408	520
3	borytuch	6.9	7.2	8.2	493	440	502
4	cewi	7	7.2	8.1	610	542	582
5	ciec	7.1	7.3	8.4	487	447	432
6	ilawa	7.1	7.3	8.1	522	526	537
7	jastarnia	7.2	7.5	8.6	567	562	527
8	klin	7.8	8.1	9	520	550	576
9	kudypy	6.8	7.1	8	522	434	439
10	milomlyn	7	7.1	7.9	524	496	523
11	mlynary	7.2	7.4	8.2	541	513	507
12	mysz	6.8	7.1	8	480	483	535
13	pborec	6.5	6.8	7.7	526	541	545
14	potr	8	8.2	9.2	526	536	560
15	resk	7.5	8	8.9	527	447	428
16	ruciane	6.7	7	7.9	497	435	432
17	siedlce	7.1	7.3	8.4	504	485	428
18	skiern	7.7	8.1	9	521	506	522
19	slowpn	7.4	7.7	8.6	510	417	447
20	stegna	7.4	7.6	8.5	548	488	474
21	walcz	7.4	7.7	8.7	491	428	423
22	warc	7.4	7.6	8.6	494	527	575
23	zytkiejmy	5.9	6.2	7.2	581	628	648