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High risk of growth cessation of planted larch under extreme drought

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Abstract

Larch trees are widely used in afforestation and timber plantations. Yet, little is known on how planted larch trees cope with increasing drought. We used a tree-ring network of 818 trees from 31 plantations spanning most of the distribution of *Larix principis-rupprechtii* to investigate how extreme drought influences larch radial growth in northern China. We found that summer drought, rather than temperature or precipitation, had the strongest relationship with radial growth throughout the region. Drought increased in frequency in recent decades, leaving a strong imprint on the radial growth of larch, particularly in dry sites. Across its distribution, radial growth in larch trees that experienced extreme droughts more frequently displayed lower resistance to drought, but higher recovery after it, suggesting these populations were better adapted to extreme droughts. Radial growth decreased with increasing drought, with particularly severe declines below a threshold Palmer Drought Severity Index (PDSI) value of -3 to -3.5. Extreme droughts (PDSI < -4.5) caused a reduction of 62% of radial growth and chronic drought events caused around 20% reduction in total radial growth compared with mean growth on the driest sites. Given that current climate projections for northern China indicate a strong increase in the frequency and severity of extreme drought, trees in large portions of the largest afforestation project in the world, particularly those in the drier edge, are likely to experience severe growth reductions in the future.

1. Introduction

Afforestation is widely advocated and used to combat desertification, air pollution, and climate change. China has strongly invested in several ambitious afforestation programs in recent years (Zhang *et al* 2016a, Chen *et al* 2019). The largest managed afforestation effort in recent history has been underway in northern China since 1978, including the 'Three North' Shelterbelt Development Program, the Beijing–Tianjin Sand Source Control Program, and the Nature Forest Conservation Program (Zhang *et al* 2016a). Larch is the fourth most used tree species in forest plantations in China, covering over 2.86 million hectares (Chinese Ministry of Forestry 2010). *Larix principis-rupprechtii* was widely planted across large areas in north-central China. Whether these planted forests can survive and thrive in increasingly dry conditions is a key factor to determine the success of one of the largest tree restoration initiatives, with potential repercussions on the global carbon cycle.

Drought stress has been widely regarded as a main trigger of decline in larch trees, particularly at the drier distribution margins (Dulamsuren *et al* 2010, Lévesque *et al* 2013, Kharuk *et al* 2019). In Asia, rapid warming has caused growth declines for dahurian larch populations at the southern margins (e.g. Zhang *et al* 2016b), while more northern populations have continued to thrive, likely due to access to permafrost water (Zhang *et al* 2019a). Recent increases in drought stress seem to have caused a shift towards higher latitudes throughout larch's natural distribution (Mamet *et al* 2019). However, little is known about the consequence of these climatic shifts on the health and distribution of larch plantations.

Planted forests are known to be particularly sensitive and vulnerable to climate change because of their simple species composition and structure (Payn *et al* 2015). For instance, scots pine has been widely used in afforestation in northeast China and while initially growing well, it has suffered serious growth declines in the past 10 years due to increasing drought (Liu *et al* 2018). Increasing water deficit, considered a key determinant of tree dieback in Chinese plantations, may result in growth declines and mortality in currently healthy forests (Song *et al* 2009). Consequently, the observed declines and dieback events in arid portions of China's planted forests may spread to wetter forests, such as those on north-central China, as temperatures continue to rise. Reduced growth and higher tree mortality would be major blows to Chinese afforestation efforts and its likelihood needs to be assessed to inform prevention and conservation strategies.

L. principis-rupprechtii is mainly distributed throughout mountain regions in north-central China in cold and humid climate conditions (Jiang *et al* 2015). The increasing severity and frequency of drought in recent decades has suppressed larch tree growth (e.g. Liu *et al* 2017). As larch's distribution is expected to shift upward and northwards with increasing drought (Mamet *et al* 2019), studying the drought response in the most sensitive parts of the distribution (low-elevations and drier edges) would offer invaluable insight into the future of these ecosystems.

Declines in growth are known to be a precursor for mortality in trees (Pedersen 1998, Cailleret *et al* 2017, 2019) and can thus be used to assess the vulnerability to further warming and drying (Desoto *et al* 2020). While planted larch forests in mesic regions of northern China seem less affected by increasing aridity, the handful of small-scale studies on climate–growth relationships in such stands prevent us from reaching general conclusions on risks of growth declines or increased mortality as the region warms rapidly (Zhang *et al* 2019b, Xu *et al* 2020). Assessing growth–climate relationship across a species' entire distribution is particularly important, because highest drought sensitivity can even occur within the core of a species' range (Cavin and Jump 2017). Forests growing in mesic regions may have lower resilience to drought than those in xeric sites, implying that dry forests may develop a range of hydrological adjustments to extreme drought (Helman *et al* 2017). The question whether planted larch in drier regions has a high resistance to drought remains unanswered.

Here, we used a tree-ring network across an aridity gradient (Palmer Drought Severity Index (PDSI) ranging from −5 to 4) in northern China to explore to what extent larch trees can tolerate drought and whether the radial growth of planted larch trees experiencing extreme drought fully recovers afterward. We tested the hypotheses that (a) radial growth responds to summer drought throughout the study region, (b) the drier portion of the study network shows stronger correlations between drought and radial growth, and (c) planted trees have lower resistance to drought in drier sites. Our hypotheses are based on the overarching framework that growth declines linked to drought are an indicator of stress, and potentially a precursor of mortality, that manifests first in drier regions, but that can expand towards wetter parts of the planted forests distributions as the climate continues to warm.

2. Materials and methods

2.1. Study area

The study area is located in northern China (36° N–42° N, 110° E–116° E, figure 1), where larch trees were planted in fertilized dark-brown soil, mainly at middle and high elevations (1200–2200 m a.s.l.; figure 1). Larch is the primary tree species in the study area. The diameter at breast height (DBH), and tree height were fairly uniform within plantations, as trees were planted in close succession on a dense rectangular grid (figure 1(b)). The understory is dominated by naturally occurring grasses in most sites (figure 1(b)).

A temperate monsoon climate prevails in the study area. According to climate records from 23 nearby meteorological stations, mean annual temperatures range from 6 °C to 13 °C. January mean temperature can be as low as −15 °C to −9 °C, while July mean temperature can reach 20 °C to 27 °C (figure 1S, which is available online at stacks.iop.org/ERL/16/014040/mmedia). Extreme low temperatures (c. −20 °C) are occasionally reached. Warming trends have been reported over the study region during the period 1988–2017 (Xu *et al* 2020). Annual total precipitation ranges between 380 mm and 560 mm and 60%–80% of it typically falls in June–August (figure 1S). Annual temperature decreases from south to north across the study area, while annual total precipitation follows a gradient from relatively dry in the northwest to relatively wet in the southeast (figure 2S). In particular, the northern and mid-eastern parts of the region are xeric, with

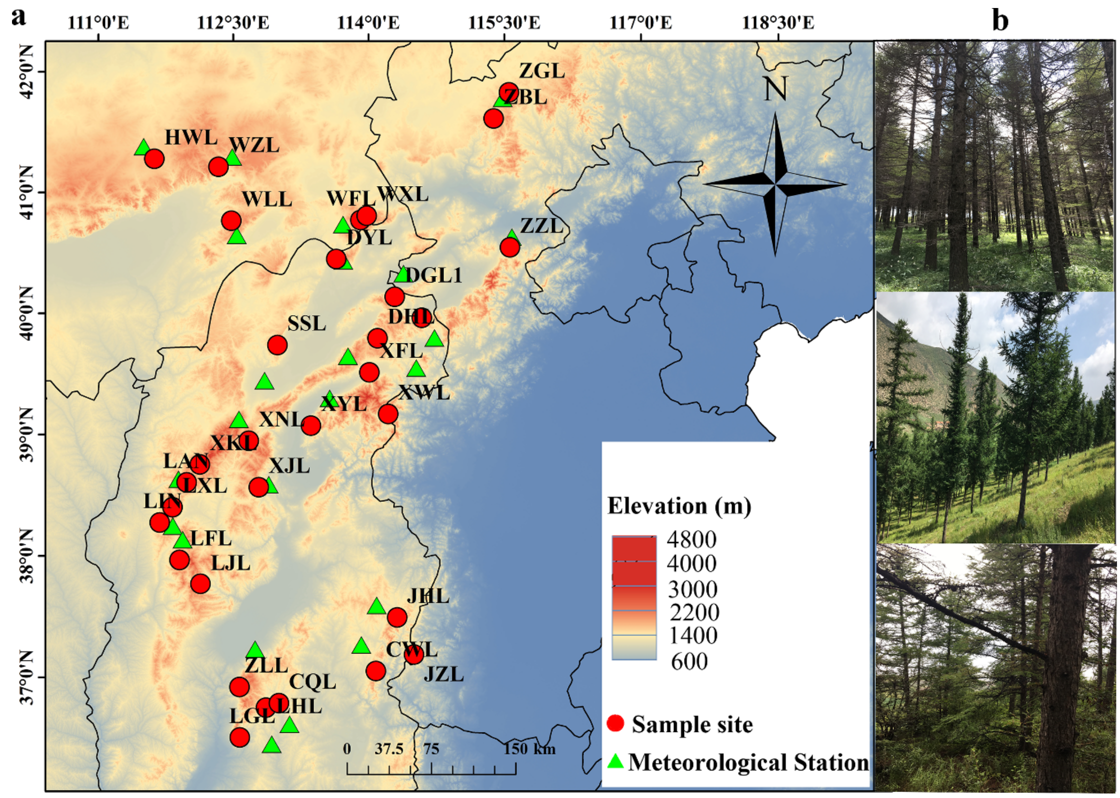

Figure 1. Location of the study region. (a) Network of 31 sampling sites (red circles) and nearest meteorological stations (green triangles). (b) Pictures illustrating forest structure and composition at our sampling sites (DHL (Hunyuan), WZL (Zhuozi), and LXL (Xingxian) sites, from top to bottom).

mean summer PDSI lower than −2.0, while the south has a more balanced water budget (figure 3S).

2.2. Sampling network and ring width measurements

We collected tree cores from 31 sites throughout the region (figure 1(b)), covering most plantations of the species in north-central China. At each site, we randomly chose 20–34 living larch trees and took two or three dendrochronological samples at breast height (1.3 m) using a standard increment borer (5.15 mm diameter, Haglöf, Sweden). In total, we collected 1613 cores from 818 trees (table 1S). Tree cores were dried and stabilized following standard dendrochronological methods, and then sanded until ring boundaries and wood structure were clearly visible. Cores were visually cross-dated, and then measured to the nearest 0.01 mm using the LINTAB 6 measuring system (Rinntech Heidelberg, Germany). The accuracy of the dating and measurements was checked using the program COFECHA (Holmes 1983).

Each ring width series was detrended in ARSTAN (Cook and Holmes 1986) using a Friedman curve with alpha = 5 to remove the influence of tree competition, topography and physiognomy (Friedman 1984, Pederson *et al* 2013). We developed 31 tree-ring width chronologies; one per site. The subsample signal strength (SSS, (Wigley *et al* 1984)) with a cutoff value of 0.75 was used to assess the confidence on the chronology due to decreasing sample depth earlier sections. The SSS was above 0.75 after the year 1987 for most sites (table 1S). The length of site chronologies varied from 19 to 60 years (table 1S). We used standard chronologies to analyze the correlation between tree growth and climate for the common period from 1989 to 2017, which 74% of chronologies covered.

2.3. Climatic data

We obtained climate data from the nearest meteorological station to each sampling site from the China meteorological administration (http://data.cma.cn). In total, we used climate records from 23 meteorological stations, spanning from 1968 to 2017. We used the self-calibrating PDSI as a metric for drought. While alternative drought indices have proven valuable, PDSI is the most commonly used index in investigations of tree growth–climate relationships, has been shown to meaningfully relate to drought classifications in the region (e.g. Yang *et al* 2017), and is widely available. PDSI data at a resolution of 0.5° × 0.5°, was downloaded from https://climatedataguide.ucar.edu/climate-data/palmer-drought-severity-index-pdsi for the period 1901–2017 (van der Schrier *et al* 2013). Considering that trees in some sites were younger than 30 years, we only used the monthly climate data for the common period (i.e. 1989–2017) in our analysis.

Monthly temperature and precipitation data from CMIP 6 model AWI-CM-1-1-MR were downloaded from the website https://pcmdi.llnl.gov/CMIP6/ under the scenario SSP126 for the period 1901–2100 to calculate the projected PDSI (Semmler *et al* 2020).

2.4. Data analysis

We calculated the Pearson correlation between site chronologies and monthly climate variables (e.g. temperature, precipitation, PDSI) from previous October to current September, as well as seasonally averaged climatic variables, which can be more representative of growing conditions than single months. The growing degree days (GDD) over 10 °C were calculated based on daily temperature for each site, to investigate the influence of annual active accumulated temperature on tree growth. GDD was calculated as the accumulated daily mean temperature higher than 10 °C using the following formula:

$$\mathrm{GDD}=\sum_{i=1}^{n} T\,(T\geqslant 10) \qquad (1)$$

where GDD is the growing degree days, T is the daily mean temperature above 10 °C, and n is the number of days when daily mean temperature is higher than 10 °C.

Resistance indicates the capacity of trees to absorb disturbance-related changes in radial growth during extreme events. Recovery reflects the trees' ability to bounce back from extreme events. Resilience describes trees' elasticity or adaptation to extreme events. To differentiate the trees' responses to drought between resistance (Rt), recovery (Rc) and resilience (Rs) in extreme drought years (i.e. average PDSI < -3.0), we used the following formulas from Lloret *et al* (2011).

$$\mathrm{Rt}=\mathrm{Dr}/\mathrm{PreDr} \qquad (2)$$

$$\mathrm{Rc}=\mathrm{PostDr}/\mathrm{Dr} \qquad (3)$$

$$\mathrm{Rs}=\mathrm{PostDr}/\mathrm{PreDr} \qquad (4)$$

where Dr is the ring-width index in the drought year, and PreDr and Post*Dr* are the mean ring-width indices during the 3 years before and after the drought year (e.g. Gazol *et al* 2018, Dorado-Liñán *et al* 2019). We tested the robustness of our results for periods of 2, 3, and 4 years obtaining similar results, thus we only report results for 3 year periods hereafter (figure 4S). The mean of Dr was calculated for consecutive drought years.

Tree growth in 15 distinct drought regimes was compared with each other to show the influences of different drought severities on tree growth. We binned the drought gradient into 15 distinct slices of width 0.5 according to the range of summer PDSI. Because PDSI values ranging from 2.5 to 4.0 were rare, we merged these bins. The relationship between the mean of tree-ring width indices and summer PDSI scales was calculated using a generalized additive model using the R package 'mgcv' (Wood and Wood 2015) to investigate how tree growth varies with drought severity. We classify drought following Yang *et al* (2017; table 2S). Strong declines in tree growth corresponded to extreme drought years. For these extreme drought years and normal condition years, the number of tracheids per radial file was counted for the Zhuozi (WZL) samples, as a case example to show the influence of drought on cambial cell division.

The spatial distribution of extreme drought (PDSI < -3.0) frequency in non-warming (1989–1998) and warming (1999–2017) periods was compared to estimate recent increases in drought frequency. Drought frequency was calculated as the percentage of years with extreme drought during the study period and in the future (i.e. based on the projected PDSI for the period 2020–2100). Future PDSI was calculated based on the projected monthly temperature and precipitation using the method of Thornwaite (1948) using the R package 'scPDSI' (Zhong *et al* 2018) for the period 2020–2100.

The percentage of total growth loss induced by extreme droughts was calculated by comparing the growth in extreme drought years with the average normal growth of the period 1999–2017 at every site. All the analyses were conducted in R v4.0 (R Core Team 2020).

3. Results

The mean annual temperature in the study area is best described as a steep change between 1997 and 1998 with relatively stable periods from 1987 to 1998 and a warmer period from 1998 to 2016 (figure 5S). However, over the last 30 years, warming was more pronounced in the northern part of our study area (i.e. at the stations of Zhuozi, Weixian, Wuzhai, Fanshi), than in the southern part (Zuoquan, Guyuan and Zhuoluo). Contrary to temperature, there was no clear trend in annual precipitation for the common period (figure 5S).

Our first hypothesis, i.e. that summer drought shows the strongest relationship with radial growth, was supported by our results (figure 2). Temperature had negative influence on tree growth, while precipitation was positively correlated with tree growth. Drought appeared to be the main climatic factor controlling larch growth in our study region, as PDSI showed stronger correlations with growth than temperature or precipitation (figure 2). Radial growth showed a clear positive correlation with PDSI of June,

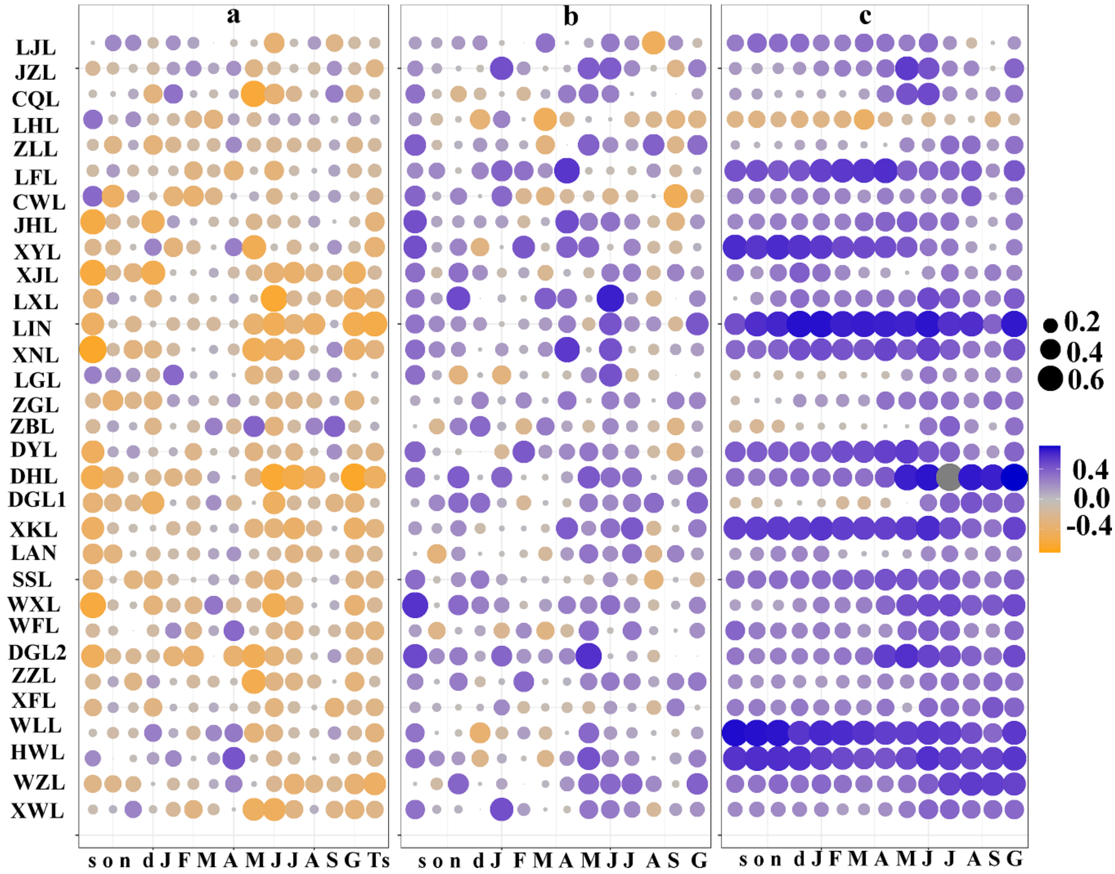

Figure 2. Correlation between tree-ring width index and monthly values of temperature (a), precipitation (b), and aridity (measured as PDSI, (c)); from previous September to current September (showcased by their initials), and growing season (Current June to August, shorted as G) for the period 1989–2017. Correlation between tree-ring width index and growth degree days over 10 °C (shorted as Ts) were detected to show the influences of cumulated temperature on tree growth. Uppercase letters indicate current year of growth, while lowercase ones indicate values on the year preceding growth. Sites are arranged from top to bottom by aridity, wet to dry. The size of the dots (upper legend) indicates the size of the correlation coefficients, while the colour (lower legend) indicates the sign of the correlation coefficients.

July, and August in 93% of sites, indicating decreasing growth with increasing drought (figure 2). This relationship was significant ($p < 0.05$) and particularly strong in the 17 driest sites of our study region (figure 2), supporting our second hypothesis that the drier portion of the study network would show stronger correlations between drought and radial growth.

Overall, the radial growth of larch was strongly influenced by drought, with reduced growth in extreme drought years and stable growth during wet years (figure 3). Ring width indices in very dry years (PDSI between −3.5 and −3.0) were significantly lower than in years with more mesic values (PDSI from −3.0 to −2.5) (t-test, $p < 0.001$), suggesting that tree growth declined progressively under drought, but was sharply affected below PDSI values of −3.0 (figure 3, table 3S). Radial growth was reduced by ca. 62% in drought years with an average PDSI below −4.5 when compared to average years (figure 3, table 4S). For example, trees grew less than 10 tracheids per radial file in such extreme drought years, compared with more than 90 tracheids per radial file in average, in normal conditions for the dry site WZL.

Tree resistance, recovery, and resilience indices were calculated for drought years (mean summer PDSI < −3.0) which generally corresponded to substantial growth reduction. Extreme drought recurrence influenced tree recovery and tree resistance to drought (figure 4). Consistent to our third hypothesis, trees had higher recovery indices under extreme summer drought. However, we found higher resistance under less extreme summer drought conditions (figure 4). Tree resilience did not change much with drought level (figure 4).

Extreme droughts occurred more frequently in the last 20 years than the 10 previous years (figure 5). The frequency of extreme drought years was higher than 30% in eight sites in last 20 years of the common period, while it was lower than 20% over the first decade of the common period (figure 5). In the future, extreme drought events are likely to occur even more frequently in the northern and central parts of our study region. The frequency of drought years was projected to exceed 40% in most sites of central

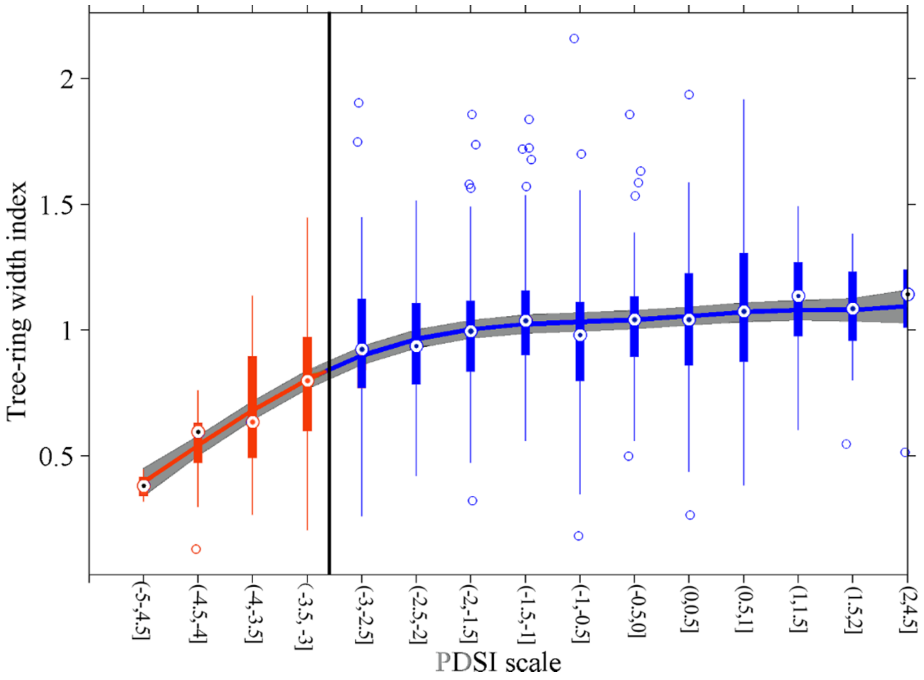

Figure 3. Tree growth distribution across drought levels. Tree growth decreasing with increasing drought, particularly in extreme dry conditions (PDSI lower than −3.0). The grey shaded area is confidence interval obtained with the generalized additive model.

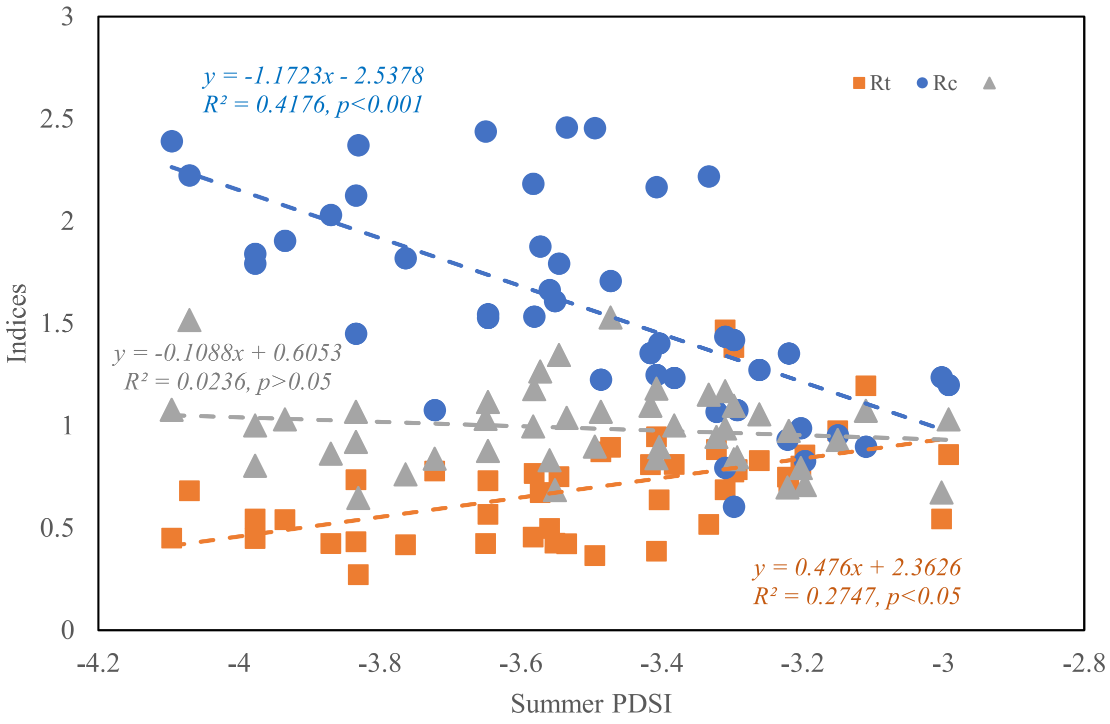

Figure 4. The relationships between recovery (Rc; blue), resistance (Rt; orange), and resilience (Rs; grey) indices with summer (June, July and August) drought. Dashed lines show linear regression curves with statistics (e.g. slope, intercept, R^2 and p-value) displayed next to the line for Rc, Rt, and Rs.

regions in the period 2051–2100 (figure 5). These drought events caused a >10% reduction in tree radial growth when compared with normal years during the past 20 years in the six driest sites (figure 6, table 4S). Growth reductions mainly occurred in northern, drier sites.

4. Discussion

4.1. Drought is an important driver across the distribution of larch in northern China

Our results showed that rapid warming has increased the frequency and intensity of drought across the

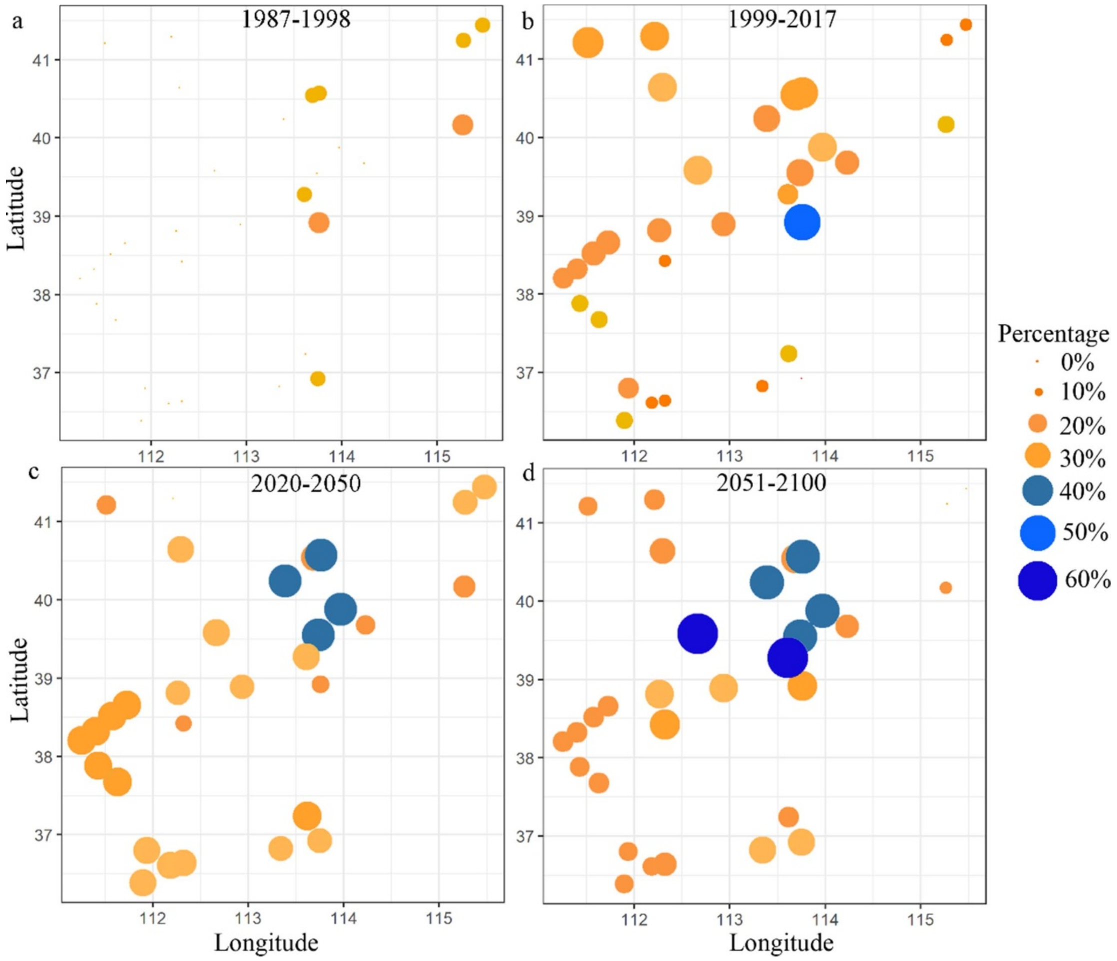

Figure 5. Comparison of percentage of years with extreme drought between the period 1989–1998 (a) and 1999–2017 (b) for each site, and future projections of drought frequency for 2020–2050 (c), and 2051–2100 (d).

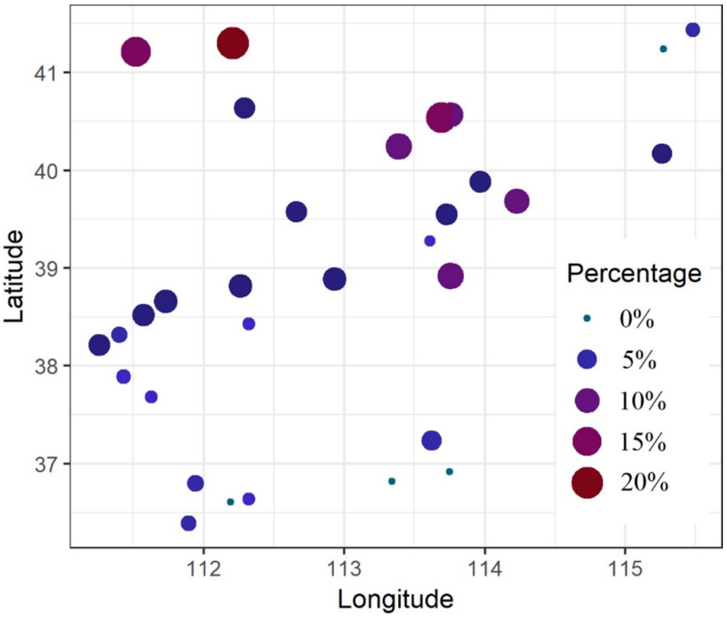

Figure 6. Percentage of total growth loss due to increasing drought events during the warming period 1999–2017 when compared with a normal years' growth in each site.

planted larch forests of northern China to the point that drought has become a more important constraint of radial growth than temperature or precipitation. Summer drought was the predominant factor influencing radial growth throughout the distribution of *L. principis-rupprechtii*, consistent with previous studies (Jiang *et al* 2015, Liu *et al* 2017, Tian *et al* 2018, Ma *et al* 2020). Summer drought is linked to soil moisture deficits, which reduce nutrient absorption and decrease water uptake and plant water status with repercussions on rates of cambial cell division and enlargement (Rennenberg *et al* 2006, Pichler and Oberhuber 2007, He *et al* 2017). Drought can also induce xylem cavitation leading to embolisms and thus growth reductions (Weber *et al* 2007, Ryan 2011). Although larch uses relatively deep soil water during the growing season (Zhang *et al* 2018), changes in water availability seem to be the main climatic constraint on larch growth.

4.2. The impact of drought depends on drought regimes within larch's distribution

Within its distribution, *L. principis-rupprechtii* shows substantial variability in drought–growth relationships. Tree growth was highly reduced in extreme drought years throughout the study region, particularly after prolonged drought. While drier sites generally showed large growth reduction and higher recovery, they unexpectedly also showed lower resistance. This pattern may arise from systematic variations in the proximity between the cavitation threshold and the lowest recurrent water potential, as tree species have rather inflexible damage thresholds to water stress (Brodribb *et al* 2020). Our results suggest that larch growth declines progressively with drought intensity, with a particular drop in growth below PDSI values of roughly −3.0. Radial growth in larch trees is severely inhibited when PDSI is lower than −4.0. Tree cores were sampled from stands of similar density, indicating that morphological and anatomical adaptations result most likely from a well-known trade-off in water transport efficiency and vulnerability (Froux *et al* 2002, Nardini *et al* 2012). This trade-off could explain why tree growth reductions were larger during extreme droughts and on drier sites.

4.3. Resistance to drought was low in drier sites, but recovery was high

Larch trees were less resistant to drought when they are exposed to more extreme droughts, but had higher recovery indices in the same instances. Drought-ending rainfall enables surviving trees to replace drought-damaged xylem by woody regrowth or xylem refilling (Brodribb *et al* 2010). Importantly, growth in wetter years does not make up for the effects of dry years due to the asymmetrical impacts of drought on growth (Dannenberg *et al* 2019). Chronic extreme drought (i.e. summer PDSI lower than −3.0 for 5 consecutive years) caused long-term tree growth reductions in larch across its distribution, but without currently leading to increased mortality. Larch trees consume water faster than many other species under soil moisture deficits (Zhang *et al* 2018). Their low capacity to restrict water loss during drought further exacerbates soil moisture deficits, potentially killing plants before the return of rainfall (Brodribb *et al* 2020). However, we only observed an impact of drought on the growth potential of planted larch forests in China.

4.4. Are growth reductions a precursor of increased mortality?

Planted larch across northern China are still young and vigorous, which may explain why trees decreased growth in drought years, but managed to recover even from chronic extreme drought. However, further increase in drought frequency (as it is projected) may lead to a high risk of growth cessation, especially in drier sites. A similar case is that of planted scots pine (*Pinus sylvestris var. mongolica*), which had grown well in sub-arid regions, but showed high mortality in recent years because of increasing drought severity (Liu *et al* 2018). Hence, increase in the severity and frequency of drought might still cause an elevated risk of tree mortality in the future when trees are getting older and the climate drier. However, if water transport adaptations are the reason for the observed differences in growth, growth itself may not be a good determinant of mortality, as growth reductions can help prevent mortality by reducing water transport and risk of cavitation (Venturas *et al* 2017). In fact, planted larch trees on drier sites are likely operating closer to their safety margin with regard to water transport, despite generally having higher recovery indices from extreme drought than wet populations. Thus, our results seem to allude to a decoupling of growth efficiency and mortality risk in these population.

Nonetheless, drought-damaged trees may be more sensitive to subsequent water shortage because of reduced xylem water delivery (Kannenberg *et al* 2019), leading to chronic tree growth declines. Chronic tree growth declines, in turn, have been shown to be the early warning of drought-induced tree death (Camarero *et al* 2015, Cailleret *et al* 2017). Possible mechanisms behind tree death during drought include vascular damage, carbon starvation, and enhanced herbivory (Choat *et al* 2018, Hartmann *et al* 2018), however, it remains difficult to identify the point where drought injury becomes lethal, making projections of future mortality speculative.

4.5. What does the future hold?

Increasing drought frequency caused substantial reductions in growth in the latest 20 years across planted larch forests in the drier edges of the species in northern China. If extreme drought becomes chronic in the future, larch trees in the drier areas of our study region have an elevated risk of future growth cessation. Thereby, chronic drought would cause pervasive shifts in forest dynamics (Mcdowell *et al* 2020). Following our results three practical steps could be taken to manage the larch plantations in drier regions: First, thinning is a possible solution to these forests during extreme drought years to promote forest resilience (Giuggiola *et al* 2016, Hood *et al* 2016). Second, more drought-tolerant tree species, ideally exploiting different soil water layers, could be planted in currently mono-specific larch plantations to transition these forests towards more resilient mixed forests. Third, planting of larch trees should be limited to sufficiently mesic regions when used in afforestation programs. Proper forest management is important to sustain the larch forests in these drier edges.

5. Conclusions

The fact that larch growth responds strongly to drought may result in large and prolonged reductions of tree growth across these planted forests under increasingly drier conditions. Our findings highlight that the growth of planted larches is susceptible to extreme summer drought while currently displaying high recovery potential. Recently increasing drought frequency and magnitude may not result in large scale forest dieback, but instead lead to substantial decline in tree growth, hence carbon sequestration reductions. Although the wetter populations do not show growth decline yet, they may not be ready for a drier future with frequent extreme droughts and therefore suffer in the future. Our results advise to reconsider using larch trees for afforestation projects in xeric regions with chronic extreme drought, as they may create unstable ecosystems susceptible to future die-offs. Species better adapted to dry conditions and which can endure occasional drought stress should be prioritized in future afforestation efforts.

Data availability statement

The tree-ring chronology data that support the findings of this study are included in the online supplementary files.

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Conflicts of interest

The authors declare that no conflict of interests exists.

Author contribution

X.Z. processed the data, analyzed the results and led the writing. X.Z., T.R., and X.H. designed the experiment and methodology. T.R., R.D.M., and L.D. wrote, reviewed and edited the manuscript. X.L., C.X., P.L., C.W., and M.H. participated in data processing and data collection.

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