FRONTIERS IN SOILS AND SEDIMENTS · RESEARCH ARTICLE

The variation and trends of nitrogen cycling and nitrogen isotope composition in tree rings: the potential for fingerprinting climate extremes and bushfires

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Abstract

Purpose Climate extremes, such as droughts and floods, have become intensified and more frequent due to intensifying climate change. Increased atmospheric carbon dioxide (CO_2) and warming-induced water limitation, as well as climate extremes, may alter carbon (C) and nitrogen (N) cycling in forest ecosystems. This provides a brief review of stable nitrogen isotopic composition ($\delta^{15}N$) in tree ring in relation to climate extremes and bushfires in context of N availability and losses in forest ecosystems.

Material and methods Tree rings were extracted from four *Pinus sylvestris* and four *Larix gmelinii* sample trees, located in a boreal plantation forest of Mohe City, Heilongjiang Province, China. Tree rings were measured to obtain mean annual basal area increment (BAI), while tree ring $\delta^{15}N$ and total N concentrations were measured on mass spectrometer at 3-year intervals. The tree ring $\delta^{15}N$ data were related to possible climate extremes and bushfires. A brief review of the relevant literature was also undertaken to support our preliminary research findings.

Results and discussion Globally, increasing atmospheric CO_2 concentration and water limitations have led to a warmer-drier climate. This has also been associated with increases of climate extremes such as drought and floods as well as bushfires. These extremes have been recorded with detrimental effects on plant and soil structures within forest ecosystems and play an important role in regulating N availability and losses in forest ecosystems. Studies of N deposition within forest ecosystems using soil and plant $\delta^{15}N$ also showed that N losses under various climate extremes can occur through direct changes in N cycling, such as increasing soil nitrification and denitrification or leaching. It is highlighted that tree rings $\delta^{15}N$ has the potential to fingerprint the intensity and frequency of climate extremes and bushfires in the forest ecosystems, but more such tree ring $\delta^{15}N$ research needs to be done in diversified forest ecosystems to confirm the potential of using tree ring $\delta^{15}N$ for quantifying the frequency and intensity of climate extremes and bushfires at both regional and global scale.

Conclusion The variation and trend of $\delta^{15}N$ in the soil–plant-climate systems are closely linked to the N cycling in forest ecosystems, and tree ring $\delta^{15}N$ has the great potential to fingerprint both intensity and frequency of climate extremes such as drought and floods as well as bushfires.

Responsible editor: Hailong Wang

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1 Introduction

Climate extremes, noted to be a necessity for the balance of the Earth's atmosphere, have become more frequent and intensified in their destructive behaviour due to global climate change (Stewart et al. 2021). Climate extremes, such as droughts and floods, potentially alter carbon (C) and nitrogen (N) cycling in terrestrial ecosystems at profoundly different timescales (Xu et al. 2009; Bai et al. 2015a, b; Choi et al. 2020). Hence, increasing environmental stress exists within forest ecosystems, decreasing plant and soil health (Stewart et al. 2021). Extreme events, such as heatwaves, floods and bushfires, can be short in duration but can have long-lasting impacts upon ecosystem function and services (Li et al. 2019, 2020a, 2021a, b; Peguero et al. 2021; Stewart et al. 2021), shaping the abundance and distribution of plant communities (Girardin 2009: Li et al. 2022a, b). Increasing temperatures and heatwaves lead to increasing intensity and frequency of droughts, which can cause a warmer and drier environment, resulting in increases in bushfires and lighting frequency (Girardin 2009; Li et al. 2021a). Increasing temperatures and heatwaves together with increased droughts have been related to tree mortality events (Li et al. 2021b, 2022b). Drought stress is a large component of global crisis in forest and plant health risks due to the lack of water availability, leading to plant dieback at a regional and global scale (Peguero et al. 2021). Flooding is also an extreme event that is detrimental to ecosystem environments, but flooding tends to increase once drought season has been completed, thus indicating seasonal or annual variations in above or below average water availability. Seasonal and annual variations in temperature and soil moisture are important determinant of growth success within plants and changes in growth ability can lead to variations of landscape distributions, physiological threshold, photosynthesis function and C and N cycling (Li et al. 2019, 2020a, b, 2021a, b, c, 2022a, b, c).

Changes and shifts in C cycle due to climate extremes have been extensively studied (Chen et al. 2008; Li et al. 2019, 2020a, 2021a, b). The N cycle is closely linked to both C and hydrological cycle (Chen et al. 2008; Li et al. 2020b, 2022c). The N_2 makes up 78% of the Earth's atmosphere (Chen et al. 2008; Bai et el. 2012; Choi et al. 2020). The reactive N depositions have contributed to the currently increasing natural CO_2 sinks in some forest ecosystems. This anthropogenic disturbance has contributed to the current changes in N and C cycles within the terrestrial ecosystems (Chen et al. 2008; Bai et al. 2012; Choi et al. 2020). Terrestrial ecosystems receive N from biological N fixation process (Guinto et al. 2000; Reverchon et al. 2012, 2020). The increases of fossil fuels and other anthropogenic uses

have led to climate change thus increasing climate extremes (Bai et al. 2015a, b; Peguero et al. 2021). This contribution can vary depending on the biotic and abiotic factors. Biotic factors include species, ages and plant components, while abiotic factors include climate change and climate extremes such as drought, floods and bushfires, having different effects on N availability and losses within terrestrial ecosystems (Rui et al. 2011; Ibell et al. 2013).

The ^{15}N natural abundance (δ^{15}N) can provide an index of ecosystem N cycling (Yoshida 1988; Sun et al. 2010; Rui et al. 2011; Ibell et al. 2013; Bai et al. 2015a). The ratio of N input or output relative to the N pools has been analysed by changes in plant and soil δ^{15}N (Yoshida 1988; Wang et al. 2015, 2020a, b, c; Choi et al. 2020; Succarie et al. 2020). Current research has also used the δ^{15}N signature as an index of N losses with interaction of bushfires, floods and drought within the soil and plant ecosystems. Differences in soil and plant δ^{15}N are closely associated with the N cycling processes such as N mineralisation, nitrification and denitrification (Handley et al. 1999; Houlton et al. 2007; Wang et al. 2015, 2020a, b, c; Craine et al. 2018; Nessa et al. 2021). The use of δ^{15}N in different N pools could assist in understanding N demands of terrestrial ecosystems (Craine et al. 2009; Perakis and Johnson 2011). The current literature has covered various aspects of using a range of methodologies, identifying climate extremes and their effects on terrestrial ecosystems. One particular methodology that is well established in the relationship of forestry health and climate is tree ring technology, which has long been used to investigate long-term tree responses to environmental and climatic change (Williams et al. 2010; Tomlinson 2015). This is analysed through the measurement of tree growth in the width of annual growth rings (Williams et al. 2010). Wide rings generally form during years of optimal climatic conditions and narrow rings occur in response to poor conditions; thus, tree rings are a well-established methodology in viewing the relationship between ring width and climate (Williams et al. 2010). To date, several studies have inferred forest responses to future climate change form statistical relationships between tree-ring record and climate variability during the life span of the tree (Williams et al. 2010; Tomlinson 2015). Basal area increment (BAI) is used to analyse tree growth and the relationship of climate change giving an accurate understanding of physiological and climatic relationship other than ring width (Williams et al. 2010; Tomlinson 2015). Stable isotopes (^{13}C, ^{15}N and ^{18}O) have been used to further understand the relationships of physiological and biogeochemical responses, carbon cycling, atmospheric CO_2, N cycling and water availability, to the increase of climate change (Williams et al. 2010; Tomlinson 2015). Due to variation in site- and

species-specific responses, tree ring methodology is providing valuable information on the long-term effects of forestry health (Tomlinson 2015).

While BAI, tree ring ^{13}C and ^{18}O have been heavily applied to understand the relationships of climate change and forest health. The ^{15}N natural abundance in the soil and plant tissues (plant ecosystems) has shown that δ^{15}N is closely linked to the importance of N cycling processes and the N balance in the context of climate change, climate extremes and bushfires (Perakis et al. 2011; Wang et al. 2015, 2020a, b). Increasing δ^{15}N in the soil is associated with losses of isotopically depleted nitrate and trace N gases and these processes can enable modelling of δ^{15}N dynamics with ^{15}N mass balance and identifying the potential pathways of N inputs and losses. However, there has been limited empirical evidence of the intensity and frequency of climate extremes within forestry ecosystems and how N cycling is affected and whether specific isotopic structures such as δ^{15}N, obtained within tree rings, can be used to fingerprint the climate extremes and bushfires (Succarie et al. 2020).

In this study, we aimed to provide a brief literature review, together with our preliminary research findings, to examine the potential of using tree ring δ^{15}N for fingerprinting climate extremes and bushfires at regional and global scale.

2 Methods and materials

2.1 Site description

Mohe City is located in northwest of the Heilongjiang Province, China (52° 10′–53° 33′ N 121° 07′–124° 20′ E). Climate in this area is subarctic, with long cold winters and short warm summers; the average annual mean temperature is −4.49 °C. The winters generally last from mid-October until April; the average temperature stays below freezing for 7 months in a year. The Heilongjiang Province is one of the largest agricultural bases in China, containing large plantation forests that are used for wood production. The plantation forest that the sample trees were collected from is the boreal forest consisting mainly of *Pinus* species and *Larix* species.

2.2 Tree ring sampling and preparation

Tree ring samples were chosen at random in the plantation forest. Four sample trees were chosen for *Pinus sylvestris var. mongolica* and four sample trees were chosen for *Larix gmelinii*. *Pinus sylvestris var. mongolica* was a dominant species in the plantation forest; hence, a larger number of sample trees were collected. In August 2018, 10–15-cm tree ring cores were collected from each sample tree. The tree ring cores were then processed (air-dried and polished) and

cross dated according to the procedures established by Sun et al. (2010) and Xu et al. (2014). The ring width was measured to 0.01-mm precision along four radii to avoid growth anomalies and then dated by using a semi-automated device TSAP-Win Scientific software system. To check for tree ring width data accuracy and the quality of cross-dating, we used the statistical program COFECHA.

2.3 δ.^{15}N measurement

Using the same sectioning for the δ^{15}N measurement, a spike was added into each sample. This N spike with known total N and δ^{15}N was added to increase the N content within the tree ring sample so that tree ring total N and δ^{15}N can be determined on the isotope ratio mass spectrometry and calculated based on the mass balance method. First, 56.6 mg of ammonium sulphate $(NH_4)_2 SO_4$ was weighted and placed into a tube containing 20 ml water, then the solution was mixed for 1 h and put into the fridge. After the spike was dried, we weighed and recorded the weight then an amount of 8–9 mg of tree ring powder was weighed and placed into the spiked tin capsules, to analyse for δ^{15}N measurement; four spikes were left without tree ring materiel as a control, using a Secron Hydra 20–22 isotope ratio mass spectrometer coupled with a Europa EA GSL sample prep system in Stable Isotope Laboratory. The equation to calculate the δ^{15}N was as follows:

$$\delta^{15}N = 1000 \times (Rsample/Rstandard)/Rstandard$$

where *Rsample* was the ^{15}N/^{14}N ratio within the sample that was given from the isotope analysis and the *Rstandard* was the ^{15}N/^{14}N ratio of the air as the reference.

3 Impacts of climate change on climate extremes and N cycling

Climate change has become a catastrophic event that has altered the Earth's ecosystems. Globally, increasing atmospheric CO_2 and water limitations are two key features of climate change, resulting in a warmer and drier future. Climate change is changing the distribution of climate extremes. This is due to increases in atmospheric CO_2 concentration, air temperatures and extreme climate events caused by combustion of fossil fuels and biomass (Amthor et al. 1995; Bai et al. 2015a, b; Savard et al. 2020). This raises a major concern on biodiversity loss and the impacts of ecosystems functioning on both regional and global scale (Amthor et al. 1995). To date, it is evident that atmospheric CO_2 concentration is influenced by both abiotic and biotic factors, such as N and water and this influence has induced a warmer and drier climate (Choi et al. 2020).

Nitrogen is another important factor that affects the productivity of the ecosystem and nutrient availability (Bai et al. 2015b). The anthropogenic creation of reactive N in 2010 has doubled compared to the rate of naturally terrestrial produced N (Savard et al. 2020; Takizawa et al. 2017; Michelsen-Correa et al. 2018; Yang 2018). Increased reactive N is through agricultural practices, such as use of fertiliser and burning of fossil fuels causing air pollution. Fertiliser has been used in agroforestry and agricultural lands to enhance plant growth through improving nutrient availability such as phosphorus and N. Increase in N inputs within the ecosystems can increase the efficiency of C sequestration of some tree species. But high rates of fertilisation can saturate the biological demand of N and lead to increased rate of N loss through leaching, denitrification and volatilisation (Takizawa et al. 2017; Michelsen-Correa et al. 2018).

High combustion of fossil fuel emissions within the atmosphere due to anthropogenic use has caused a decline in forestry health. High pollution rates have led to acid deposition. Acid deposition is slow through long-term chronic influences and can only be detected once visible symptoms appear. Chemical signatures that are sensitive to the acid deposition is a helpful indicator for forestry health (Yang 2018; Katahata 2007). With an increase in N availability within soil due to fertiliser, it is expected to result in the imbalance of N sources within soil structure thus potential leading to N losses via denitrification and leaching which many agricultural lands have found to be an increasing problem with crop growth and soil health, leading to much higher soil and plant $\delta^{15}N$ (Denk et al. 2017).

The reactive N depositions contribute to the currently increasing natural CO_2 sinks, in forest ecosystem especially, as well as increases in the production of N_2O within soil environments due to the lack of energy and nutrients that could not be observed by microbes. During the same interval as the CO_2 concentration, N_2O has increased by 20% from 271 to 324 ppb in 2011 (Portl et al. 2007; Bai et al. 2015a, b). This increase can possibly shift our prediction of the effects of climate change and its relationship to N. Current literature on climate change shows a higher frequency and intensity of various climate extremes such as droughts, floods and bushfires (Sun et al. 2010; Fu et al. 2020). Thus, climate change and climate extremes have been concluded to alter N cycling and transformation as well as C cycling within terrestrial ecosystems. This highlighted a need to further understand the relationship of increased climate change to acceleration of climate extremes and their effects on

soil N transformations (Sun et al. 2010; Xu et al. 2014; Fu et al. 2020; Succarie et al. 2020; Liu et al. 2021).

4 Tree ring analyses on the long-term effects of climate change and their relationship with the N cycling process

Annual tree ring chronologies can date the effects of climate change and long-term temperature records going back centuries. Using tree ring basal area increment (BAI) and stable isotope compositions, we can construct tree physiological responses to climate change (Sun et al. 2010; Xu et al. 2014; Fu et al. 2020; Liu et al 2021). The carbon isotopic composition ($\delta^{13}C$) of tree rings is a sensitive proxy for water availability and can provide historical records of intrinsic water use efficiency (WUEi) (Farquhar et al. 1982; Tomlinson 2015), which was also used to define the ratio of net photosynthesis to transpiration. These proxies are affected and correlate with changes in climate, atmospheric CO_2 concentration, air pollution and nutrient availability (Peri et al. 2012; Tomlinson 2015).

The $\delta^{15}N$ is a proxy for N losses and availability in the forest ecosystems which is used to define the N deposition within forest ecosystem (for example, see Fig. 4) (Sun et al. 2010; Tomlinson 2015). Changes in soil–plant $\delta^{15}N$ can provide an index of ecosystem N cycling. The ratio of N input or output relative to the N pools has been analysed by changes in plant and soil $\delta^{15}N$ (Hart et al. 2003; Craine et al. 2009; Perakis 2011). Current research has also used the $\delta^{15}N$ signature as an index of N losses and fixation within soil and plant ecosystems (Koba et al. 2003; Portl et al. 2007). Differences in $\delta^{15}N$ values are closely associated with the N cycling processes such as N mineralisation, nitrification and denitrification which have been represented in Fig. 1 (Handley et al. 1999; Houlton et al. 2007; Craine et al. 2018). A recent study has found the use of $\delta^{15}N$ and climate extremes and bush fires, within sediment samples as a measure of the effects of water availability and N cycling due to climate change (Gosling et al. 2022). The $\delta^{15}N$ was recovered from sediment, providing a historical record of fire activity and moisture availability, compared with atmospheric CO_2 data and temperature of the region. This indicates the potential relationship between $\delta^{15}N$ and climate extremes (Kast et al. 2019; Gosling et al. 2022). Within the literature, there is an abundance of experimental design of using $\delta^{15}N$ as an indicator for long-term responses of N cycling, water availability and soil and plant health. The $\delta^{15}N$ has been extracted form soil material, foliage and other plant tissue; however, there is little research of using tree ring $\delta^{15}N$ to fingerprint the frequency and intensity of climate extremes and bushfires.
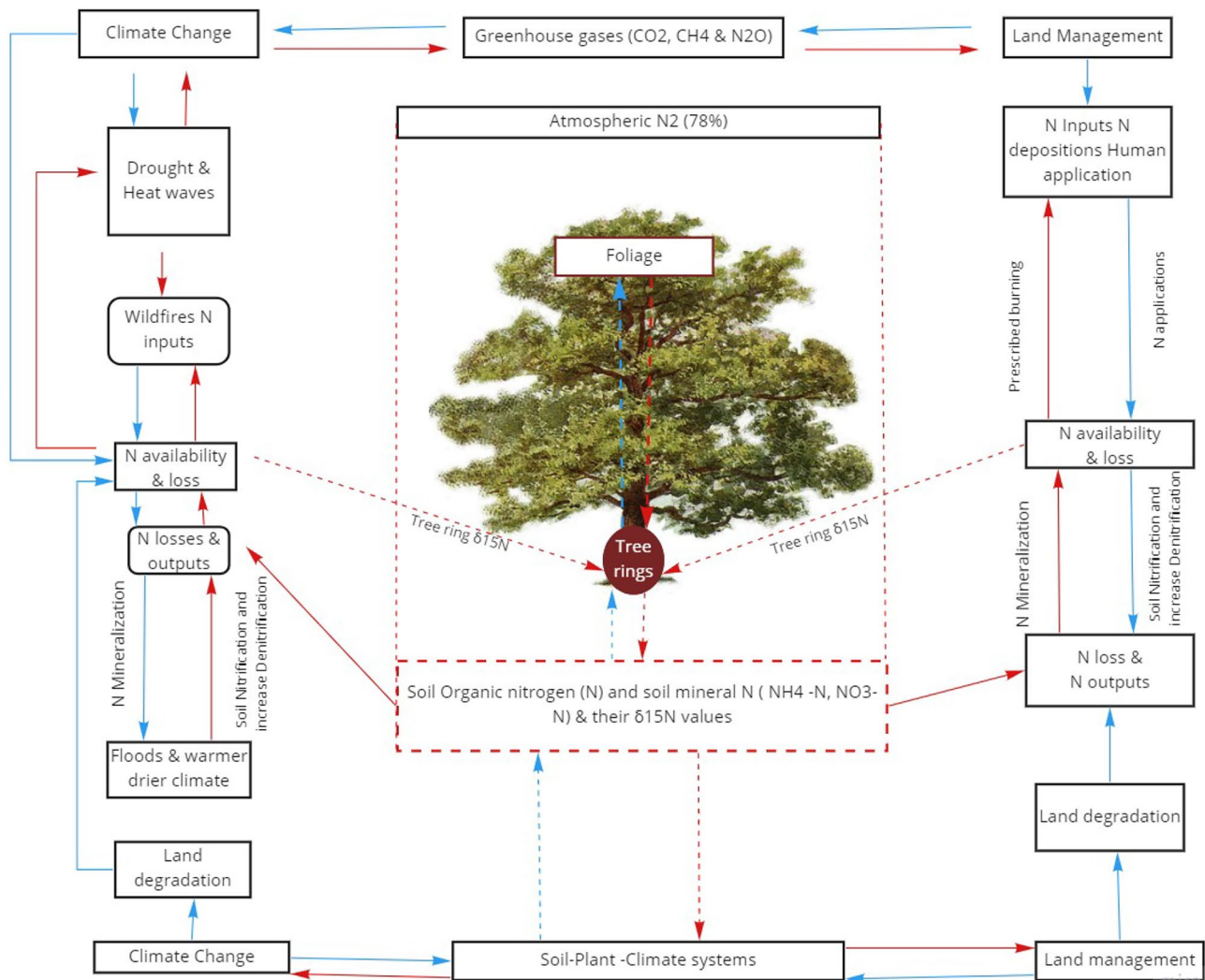
Fig. 1 Schematic model of N loss and availability affected by climate extremes and land degradation as fingerprinted by tree ring N isotopic composition ($\delta.^{15}$ N)

5 Tree ring $\delta.^{15}$ N as an indicator of intensity and frequency of climate extremes and bushfires

5.1 Droughts

Drought has been a global extreme that has affected many ecosystems and agricultural habitats with the increase of temperature and reduction of seasonal water availability, while the frequency and intensity of drought have increased (Sardans et al. 2020; Looney er al. 2021). Drought events cause water stress within the soil–plant systems, which can reduce photosynthesis and cause resistance of CO_2 diffusion to the chloroplast and metabolic inhibition through stomatal closure (Looney et al. 2021). The high salt content within the chloroplasts leads to inadequate photosynthesis which can transfer to photorespiration and have a detrimental effect on

the mitochondrial metabolic synthesis (Sardans et al. 2020). This can also lead to lower levels of nutrient uptake and energy uptake due to the lack of C thus reducing the N mineralisation, respiration, nitrification and soil moisture (Xue et al. 2020; Zhang et al. 2021; Peguero et al. 2021). Both NO_3^--N and NH_4^+-N are sensitive to dry conditions, since N mineralisation, nitrification, denitrification and NO_3^--N leaching are decreased (Lennon et al. 2017; Peguero et al. 2021). Current literature has shown that drought can influence the N input and output within the terrestrial ecosystems. Due to the lack of water content, soil N transformations are generally very low within the soil, thus with little N losses (Zhang et al. 2021). Under drought conditions, there would be high nitrification and soil and plant δ^{15}N would be expected to be very low (Ibell et al. 2013; Wang et al. 2015, 2020a, b, c; Nessa et al. 2021). These indicate the relationship that has been measured within current literature on the
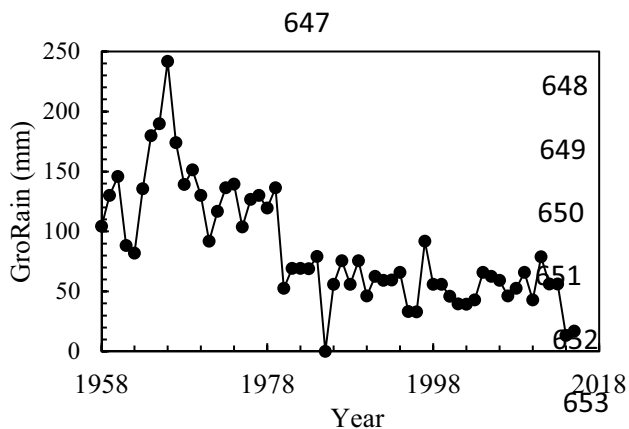
Fig. 2 Mean annual growing season rainfall (GroRain, mm) during 1958–2016 ($n=57$) for the study site in Northern China

implication and relationship between N transformation and cycling and drought events in soil and plant systems using soil $\delta^{15}N$.

It is expected that lower tree ring $\delta^{15}N$ values would be detected under drought conditions since there would be little N mineralisation and hence little available mineral N to be lost via soil nitrification, denitrification and leaching (Figs. 2 and 3).

5.2 Bushfires

Bushfires is a detrimental event that is triggered by climate change and increased drought and a warmer-drier climate. Increasing bushfires, due to climate change and drought, N fertilisers and burning of fossil fuels can increase the amount of N gas emissions to the atmosphere (Aber et al. 1998; Choi et al. 2020; Wang et al. 2020a, b, c). However, to date, unlike the C cycle, there is limited understanding of increasing bushfire impacts on the N cycling in terrestrial ecosystems (Lavorel et al. 2007; Wang et al. 2018, 2020a, b, c; Nessa et al. 2021; Taresh et al. 2021).

Due to high N inputs from the N depositions, most of the deposited N in the soil would be lost via soil nitrification—denitrification and leaching, resulting in higher $\delta^{15}N$ values in soil ammonium N and nitrated N (Wang et al.

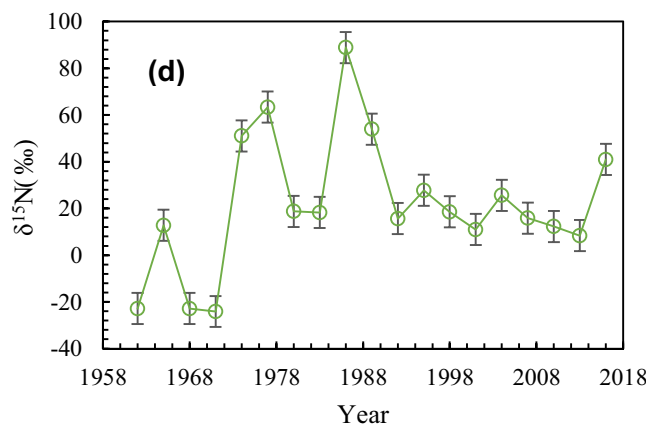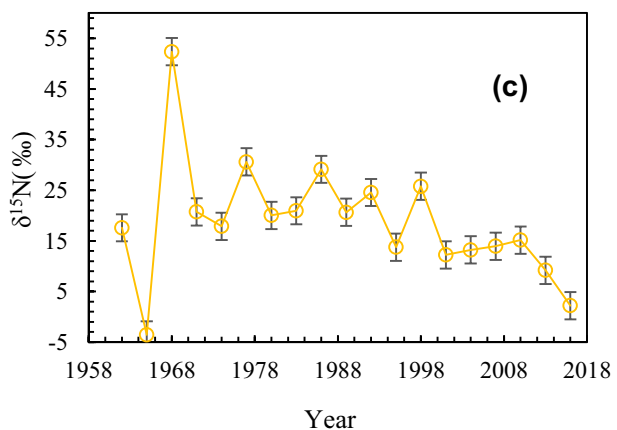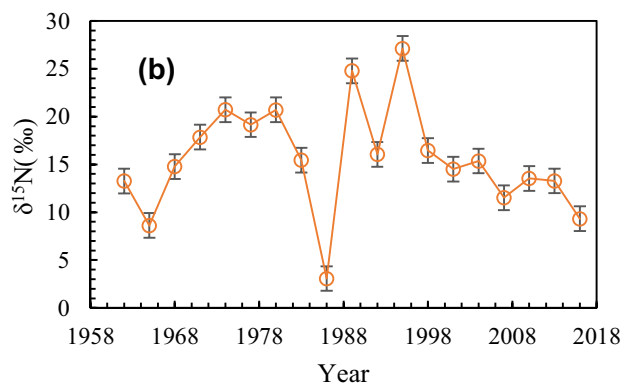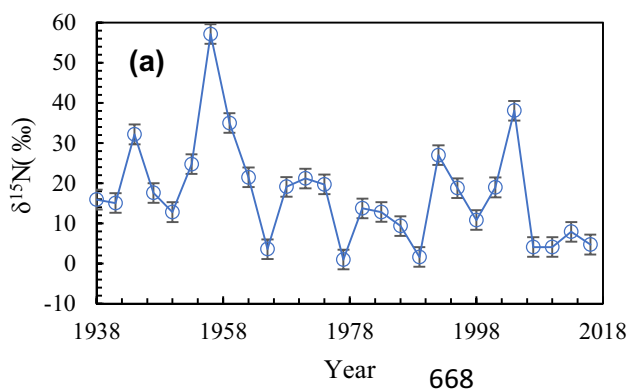**Fig. 3** Impacts of climate extremes and bushfires during lifespan of *Pinus sylvestris* on mean annual ^{15}N natural abundance ($\delta.^{15}N$, ‰) in tree ring samples (averaged at 3-year interval) for sample tree 1 (81 years old in 2018) (**a**), sample tree 2 (57 years old in 2018) (**b**), sample tree 3 (57 years old in 2018) (**c**) and sample tree 4 (57 years old in 2018) (**d**) in Northern China

2015, 2020a, b, c). The $\delta^{15}N$ in the soil (plant ecosystems) is closely linked to the important N cycling processes and the N balance in the context of climate change and increasing bushfires (Perakis et al. 2011; Wang et al. 2015, 2020a, b, c). Increasing $\delta^{15}N$ in the soil is associated with losses of isotopically depleted nitrate and trace N gases and these processes can enable modelling of $\delta^{15}N$ dynamics with ^{15}N mass balance and identify potential pathways of N inputs and losses. This would be much easier to measure than direct measurements of N deposition and losses of N gases by denitrification (Perakis et al. 2011); Masse et al. 2016).

The $\delta^{15}N$ can be used to evaluate the bushfire events and major site disturbances (such as logging and thinning) to understand the N balance and dynamics in terrestrial ecosystems. However, there is still uncertainty of the long-term effects of such disturbances on N balance in an ecosystem (Perakis et al. 2011). The N availability is an important indicator of forest health (Aber et al. 1998). The N deposition in the 11% of the world's forest ecosystems has exceeded the critical threshold (Delwiche 1970; Cleveland et al. 1999). From 1980 to 2010, the average N bulk deposition increased in China by 60% (Liu et al. 2021). Given the limited supply of N in terrestrial ecosystems (Delwiche 1970; Aber et al. 1998), N deposition is an important driver for ecosystem respiration across all biomasses. Water stress can also influence N limitations, reducing tree capacity to assimilate atmospheric CO_2. With this in mind, understanding the effects of major bushfires on $\delta^{15}N$ and N cycling in terrestrial ecosystems has become increasingly important (Wang et al. 2015, 2020a, b, c; Succarie et al. 2020).

Previous studies have reported that an indicator of long-term bushfires can be observed in tree ring $\delta^{15}N$, via looking at the fire history reconstruction by comparing long-term, sedimentary charcoal with nearby fire scar chronologies (Holz et al. 2012). There is little literature on relationships among tree ring $\delta^{15}N$, total N concentration and bushfires, with most of the research that has been done about bushfire impacts on $\delta^{15}N$ and N cycling processes in the soils (Wang et al. 2015, 2020a, b, c). In our preliminary study (Figs. 2 and 3), we have successfully used tree rings $\delta^{15}N$ to fingerprint the 1986 bushfires in Da Xin An Ling mountains of Northern China, with tree ring $\delta^{15}N$ higher when the trees samples were closer to the burned areas.

Our results have given insights into the current gaps in N depletion due to major bushfires as well as the high and low peaks of N availability in the recorded lifespan of the chosen species in boreal forests. The results answered both our questions that were made in the study aims to test whether the neighbouring forest would record the 1987 major bushfires in the affected area by tree ring $\delta^{15}N$. When measuring the tree ring $\delta^{15}N$ in each 3-year interval of each sample tree for each species, they all had increases and decreases in tree ring $\delta^{15}N$, indicating that N depletion was not only shown in
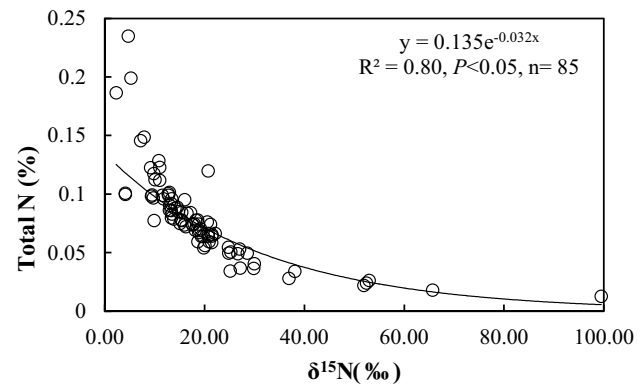

Fig. 4 Relationship between total nitrogen (N) concentration (%) and ^{15}N natural abundance ($\delta.^{15}N$, ‰) in tree rings of *P. sylvestris* in Northern China

the soil but also in the tree rings (Figs. 3 and 4). In this study, tree ring $\delta^{15}N$ and total N concentration of *Pinus* species were more sensitive to ecosystem N availability, which could be significantly influenced by major forest disturbances such as harvesting, thinning and bushfires (Fig. 4).

5.3 Floods

Considerable evidence of high temperature has led to precipitation extremes increasing in magnitude and frequency, further leading to flood hazards (Veijalainen 2010; Nolin 2021). Floods account for 84% of all-natural disaster global death, and with the increase of temperature it has been recorded with increasing flooding events (Takai and Kamura 1966; Milly 2002; Panahi 2021). There has not been a clear definition, as to whether the floods are caused by climate change or natural process. Whether climate change has caused and increased flood intensity and frequency, and how this is affecting the ecosystems have also not been fully understood. Current literature has measured flood hazards with high levels of seasonal precipitation within various forest types and climate zones such as tropical, subtropical, temperate, boreal, Mediterranean and arid zones (Escher et al. 2004; Nolin 2021), indicating more of a historical flooding, rather than floods that have been increased by climate change. Flooded soil has the potential losses of N due to high levels of denitrification a major source of greenhouse gases (Reddy 1990; Bei et al. 2013; Zhou 2020). Saturation of water due to flooding affects the supply of oxygen within soil and oxygen is generally decreased (Davidsson 1996; Pu et al. 2002). Oxygen is the main factor to regulate denitrification, soil nitrification and when there is a lower supply of oxygen the second important factor is $NO_3^- N$ as an external source, which requires a larger amount of energy, and with the lack of C and energy sources this can prove detrimental (Kozlowski 1984; Davidson et al. 1996; Zhou 2020). In the

absence of oxygen which may occur when roots are flooded, flooding can induce oxygen deficiency because oxygen is difficult to diffuse in water (Unger et al. 2009; Shen and Chui 2021).

Flooding is one of the dominant mechanisms leading to the O_2 depletion and low redox conditions, by greatly retarding the diffusion of soil matrix, while flooding can cause O_2 demand to exceed that of diffusive resupply leading to anaerobic conditions (Unger et al. 2009; McNicol and Silver 2014). Flooding can change the soil pore-space phase gas to liquids and alter the physicochemical environments (Mitchell and Soga 1993; McNicol and Silver 2014). Increased soil matrix connectivity under flooded conditions could connect microbes to dissolve solutes, which could enhance lower soil tortuosity and stimulate NO_3 reduction and increase N_2O production (Patrick and Reddy 1976; McNicol and Silver 2014; Fujiyoshi et al. 2019). In short, flooding events would be expected to result in major N losses via denitrification and leaching, leading to much higher soil and plant $\delta^{15}N$; thus, it is important to further understand if the intensity and frequency of floods have been increased due to climate change, which possibly can be recorded and shown in tree ring $\delta^{15}N$.

The study of the anatomy of growth rings in trees directly expose to seasonal floods can provide quantitative and continuous predictors of seasonal climate in forestry ecosystems (Nordin et al. 2001; Nolin 2021). The traditional understanding of this proxy is through observing flood ring which is an anatomical change in earlywood vessels associated with the physiological responses to anoxia during persistent flooding (Nordin et al. 2001; Oh 2008; Nolin 2021). As shown in Fig. 3a-d, there are various peaks of tree ring $\delta^{15}N$ indicating a change in N availability and N losses. Once comparing the precipitation high peaks with the $\delta^{15}N$ high peaks it gives an indication that these peaks are due to high precipitation essentially flooding, these high peaks show the intensity of flooding within the area, causing high N loses within the soil via denitrification and leaching as mentioned above (Figs. 2 and 3), each individual plant can have a slight variation of the peaks due to ageing and where they were positioned within the forest due to the soil N variability, some species/individuals that are more sensitive could indicate a higher exposure to the flooding as shown in Fig. 3a, d, which show larger peaks than Fig. 3b, c. Our preliminary tree ring $\delta^{15}N$ study represents the first attempt to use tree ring $\delta^{15}N$ for fingerprinting the climate extremes of droughts and floods as well as bushfires, but more research would need to be done in different forest ecosystems to confirm the potential of using tree ring $\delta^{15}N$ to reconstruct the past climate extremes and bushfires as compared with the other approaches

(Figs. 2 and 3). It is also interesting to note that there would be negative, nonlinear relationships between tree ring $\delta^{15}N$ and tree ring N concentration or N availability, highlighting higher tree ring $\delta^{15}N$ due to higher N losses and lower N availability (Fig. 4).

6 Conclusions

The literature review and our preliminary research findings have highlighted that the $\delta^{15}N$ in soil–plant system is a very powerful indicator of major biotic and abiotic factors influencing the ecosystem N losses and availability, and tree ring $\delta^{15}N$ offers exciting and novel approach for fingerprinting the climate extremes (particularly drought and floods) and bushfires in forest ecosystems. It has the great potential to use tree ring $\delta^{15}N$ for quantifying the intensity and frequency of climate extremes (particularly drought and floods) and bushfires in the context of intensifying climate change and land use.

Declarations

Competing interests The authors declare no competing interests.

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