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### Anthropocene

journal homepage: www.elsevier.com/locate/ancene

Invited research article

# Warfare dendrochronology: Trees witness the deployment of the German battleship *Tirpitz* in Norway

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#### ARTICLE INFO

Article history: Received 29 January 2019 Received in revised form 29 April 2019 Accepted 1 May 2019 Available online 18 May 2019

Keywords: Second World War Anthropogenic impact Pollution Smoke screen Tree ring Forest disturbance

#### ABSTRACT

War has an immediate and obvious effect on people and communities, but its impacts on local ecology can be more subtle. This paper shows how one military encounter in the Second World War has left a clear legacy in the northern forests of Norway, trackable more than seventy years later. We used annual growth rings of ~180 pine and ~30 birch trees as witnesses of the deployment of the German battleship *Tirpitz* at the Kåfjord. The *Tirpitz* was the target of several Allied air attacks, but the *Kriegsmarine* (German navy from 1935 to 1945) used artificial smoke, consisting of chlorosulfonic acid and zinc/ hexachloroethane, to hide the ship. These smoke-screen actions throughout 1944 caused pine forests surrounding the Kåfjord to exhibit a strong and unusual growth decline. The tree damage extended up to 4 km away from the *Tirpitz*. In the most extreme case, growth was interrupted for nine years. 'Warfare dendrochronology' could help to evaluate potential environmental impacts of the Second World War on forest health and composition elsewhere in the European theatre.

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#### 1. Introduction

Warfare is a central and unique feature of *Homo sapiens* L. and has been part of human cultures and civilizations for thousands of years (Machlis et al., 2011; Francis and Krishnamurthy, 2014). Obviously, war leads to tragedies for societies and human suffering, but also poses a great threat to the environment and most living organisms (Farina, 2011). The fact that war leads to undesirable environmental impacts, including the (un)intentional destruction and degradation of natural resources, such as forests, crops and water resources, has long been recognized (Hupy, 2008; Machlis and Hanson, 2008; Reuveny et al., 2010; Hanson, 2011; Francis and Krishnamurthy, 2014). Ecological consequences can be generated during all three stages of war — preparation of war, war (violent conflict), and post-war activities (Machlis and Hanson, 2008) — and environmental damage is generally accepted as unavoidable collateral damage (Marler, 2013).

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http://dx.doi.org/10.1016/j.ancene.2019.100212 2213-3054/© 2019 Elsevier Ltd. All rights reserved.

War has affected forests for millennia (McNeill, 2004). Roman accounts describe massive forest fires set by Germanic barbarian tribes to confuse and frighten their enemies, but the Romans themselves also used fire as a weapon in what is now France and Germany (Hupy, 2008). The era of modern chemical weapons in World War I (WWI) and the associated effects on forests reached a new level beyond simple burning. The Battles of Verdun and Ypres at the Western Front devastated forests in France and Belgium through stationary combative activities (Freedman, 1995; McNeill, 2004; Hupy, 2008). Names for some regions as "place à gaz" (gas place), "Forêt de Guerre" (War Forest) or "Zones Rouge" (Red Zones) still bear witness to the heavy and persistent environmental destructions. Even though explosion of ordnance itself had likely destroyed the forest, chemical warfare agents additionally contaminated these battlefields. These agents includes chlorine, phosgene/diphosgene, arsenicals and lachrymator, mostly contained in artillery shells (Thieme, 1998; Bausinger and Preuß, 2005; Bausinger et al., 2007; Prestidge, 2013). During the Greek Civil War in the late 1940s, napalm was used to burn down the forests in the Pindus Mountains of northern Greece, which served as refuge for rebel forces (McNeill, 2003, 2004). More recently, the Second Indochina War represents one of the most prominent and



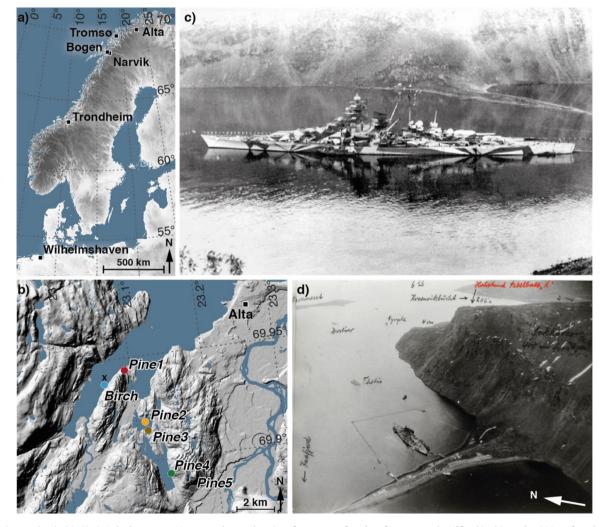




obvious forest devastations ever conducted by humans. With the application of chemical anti-plant herbicide and defoliation chemicals, including Agent Orange, ~22,000 km<sup>2</sup> of Vietnamese forests (23% of all forested area in the country) were intentionally destroyed (Orians and Pfeiffer, 1970; McNeill, 2004; Westing, 2012 and references therein).

Scientific studies on the environmental impact of warfare on forests are still scarce, however, especially for WWI and World War II (WWII). Historical writings provide some assessments, but these documents focus on the environmental factors influencing battles rather than the effects of war on the environment (Hupy, 2008). Photographs, paintings, or first-person accounts that allow an appreciation of the intensity of forest devastation also enable assessment of the ecological effects of warfare (e.g. Parsons, 1919, also see Freedman (1995) for other examples). Studies using proxy archives to evaluate military related forest devastation are rare, except a stalagmite from Northern Italy, which indicates deforestation coinciding with pre-WWI military activities (Borsato et al., 2007). An archive that scholars have not used yet to identify the impacts of military conflicts on forest ecosystems are tree rings. Only one study used dendrochronology to identify the wood supply for trenches at the above mentioned Western Front during WWI (Haneca et al., 2018). Trees record environmental changes and impacts in high temporal resolution (Fritts, 1976), offering tree-ring research the potential to steadily expand its application areas (Büntgen, 2019). Tree-ring width is a parameter representing the tree's vitality (Dobbertin, 2005), thus it enables assessment of damage through environmental disturbance. This paper introduces the general approach of 'warfare dendrochronology', which should be defined, as a previously unrecognized tool to evaluate the effects of warfare on local environments and forests specifically.

In this case, the theatre of war is the Kåfjord in northern Norway. There, the *Tirpitz*, the largest battleship in the *Kriegsmarine* (German navy from 1935 to 1945), was moored for several months during the latter stages of WWII in 1943 and 1944 (Fig. 1). The ship loomed as a constant threat to Allied shipping and, as a consequence, was the target of several Soviet and British efforts to sink the giant battleship. In this article, we first provide detail on the ship and its history, as well as the strategy employed by the



**Fig. 1.** The German battleship *Tirpitz*'s deployment to Norway and target locations for surveys of modern forests near the Kåfjord in this study. a) Map of northern Germany and Scandinavia showing Wilhelmshaven (Germany), where the *Tirpitz* was commissioned on February 25, 1941, and the Norwegian fjords used by the *Tirpitz* as moorings from January 15, 1942 onwards. From September 9, 1943 to October 15, 1944 the battleship was moored in the Kåfjord close to Alta (as shown in Fig. 1b). b) Map of the Kåfjord close to Alta in northern Norway and the tree-ring sampling sites in this study. One of the *Tirpitz*'s moorings at the Kåfjord (as shown in Figs. 1 d and 2 b) is marked with a cross. c) Photograph of the *Tirpitz* (with dazzle camouflage employed) moored in the Kåfjord (© John Asmussen). The sampled birch stand is visible in the background. d) Photograph of the Kåfjord, June 1944 (© Tirpitz Museum). The red script in the upper right is a note indicating the placement of German smoke batteries. During the 2016 and 2017 study field campaigns, we observed remnants of smoke-generating equipment at this location (Fig. 2 c and d), which corresponds to our *Pine1* sampling site. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

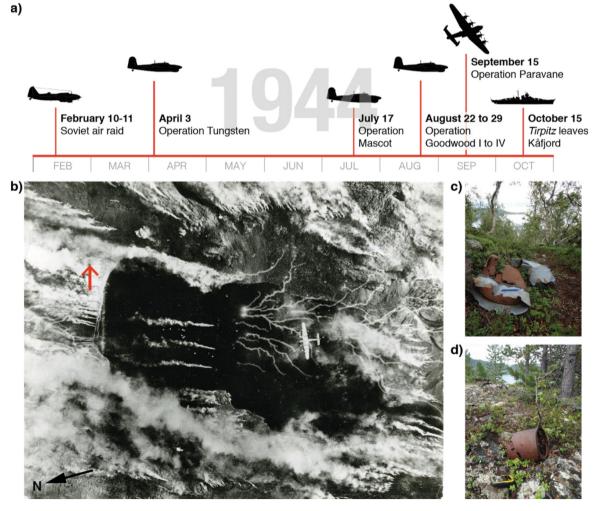
*Kriegsmarine* to use 'artificial smoke' to conceal the ship's location. Then, we detail our study of more than 200 trees at the surroundings of the Kåfjord (Fig. 1b). We addressed the following research questions: (1) How did the Tirpitz battles affect local forests? (2) What was the spatial impact and duration of those effects? (3) Did they have different effects on the two main tree species pine and birch? We report how we applied dendrochronological techniques to assess biological damages due to this smoke, which is still visible in the trees 70 years later.

## 2. The battleship *Tirpitz* and its attacks and defence in northern Norway

Two thousand tons heavier than her sister ship the *Bismarck*, the *Tirpitz* was the largest ship in the *Kriegsmarine* during WWII. Commissioned on February 25, 1941 in Wilhelmshaven, Germany, the *Tirpitz* had a length of 251 m, a crew compliment of 2,500, and displaced 53,500 tons fully loaded (Koop and Schmolke, 1990). Shortly after its completion, Germany invaded the Soviet Union and the *Tirpitz* was appointed flagship of a temporary Baltic Fleet tasked with limiting Soviet naval operations out of Leningrad. On January 14, 1942, the *Tirpitz* was redeployed to Norway. Its orders were to attack supply convoys bound for the Soviet Union, draw

attention from British naval assets, and deter any potential Allied invasion. Despite its capabilities, the battleship was rarely involved in operational deployments, so that Norwegians dubbed her "Lonely Queen of the North". As the *Tirpitz* posed a constant threat to Allied convoys in the Barents Sea, Winston Churchill, Prime Minister of the United Kingdom, preferred to refer to the ship as "The Beast". Early in 1942, Churchill named the *Tirpitz* as the top priority for the British maritime campaign: "The destruction or even the crippling of this ship is the greatest event at sea at the present time. No other target is comparable to it." (Winston Churchill, January 25, 1942)

The *Tirpitz* changed her mooring in the fjords of Norway several times, first in Trondheim, then Narvik, followed by Bogen (Fig. 1a). But the fjord the *Tirpitz* anchored most (from September 9, 1943 to October 15, 1944) was the Kåfjord close to Alta (Norway) (Fig. 1). In an effort to remove Germany's last serious surface threat, the Allies launched a variety of attacks with miniature submarines and carrier-based aircraft (Zetterling and Tamelander, 2009). In 1944, the Allied planned several operations to sink the *Tirpitz* at the Kåfjord. While bad weather forced cancelation of some aerial attacks before the planes reached the Kåfjord, nine aerial sorties were able to reach their target location (Fig. 2a). Most air attacks did not result in direct bomb hits. Only during "Operation



**Fig. 2.** Smoke screen actions at the Kåfjord. a) Timeline of the aerial attacks to the *Tirpitz* at the Kåfjord (Frère-Cook, 1977; Sweetman, 2001). b) Aerial photograph taken by the British Royal Air force during "Operation Paravane" on September 15, 1944 (© Tirpitz Museum). The white silhouette of a British Lancaster heavy bomber is visible in the centre right of the image. Due to the heavy smoke screens, the *Tirpitz* cannot be seen but her mooring location (same as in Fig. 1d) is marked with a red arrow. c) "*Nebelzerstäuber*" (smoke sprayer) and d) "*Nebelkerze*" (smoke candle) remnants found at *Pine1*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Tungsten" and, after very massive attacks within seven days in August, "Operation Goodwood III" led to direct hits on the *Tirpitz*. Finally, bombing damage to the ship caused by "Operation Paravane" was so severe that the Germans decided not to repair it comprehensively, but instead to use it as a floating flak battery. One month later, the *Tirpitz* sailed by its own power out of the Kåfjord and went to the island Håkøy near Tromsø. Following yet another unsuccessful British attack on October 29, 1944, the Royal Air Force finally destroyed and sunk the ship on November 12, 1944 (Frère-Cook, 1977; Sweetman, 2001).

During these attacks, among other actions of defence, the Nazis attempted to hide the *Tirpitz* using artificial fog (or smoke screens) to obscure its position from aerial bombers. In the Kåfjord, the first trial of this anti-aircraft defence method was conducted on January 14, 1944. Dozens of smoke batteries were located at the slopes of the Kåfjord (see, e.g., the writing highlighted in red in Fig. 1d referring to smoke batteries), and about 20 fishing boats were loaded with smoke-producing devices (Sweetman, 2001). When engaged, the generators produced smoke for up to 4.5 h (Hampe, 1963). The smoke screening was very efficient, and documents report the system was used in response to every aerial attack attempted (except for the Soviet air raid in February 1944), leading to the high number of unsuccessful operations mentioned above. For "Operation Mascot", for example, the British squadron leader reported that the Tirpitz was completely covered with fog within nine minutes. By the end of the encounter, the entire Kåfjord was covered up to an elevation of 300 masl (Frère-Cook, 1977; Sweetman, 2001). Fig. 2b, an aerial picture of the Kåfjord during "Operation Paravane" illustrates the extent of the smoke screens (the *Tirpitz* is not visible, but her mooring is marked with a red arrow, which is the same location as in Fig. 1d). The actual frequency of smoke screening (including military exercises) at the Kåfjord cannot be reconstructed with certainty.

Due to the remnants still lying at the surroundings of the Kåfjord today, we know that the Kriegsmarine used at least two different kinds of smoke generators: smoke sprayers ("Nebelzerstäuber", Fig. 2c) and smoke candles ("Nebelkerze", Fig. 2d). The smoke agent for smoke sprayers was chlorosulfonic acid (HSO<sub>3</sub>Cl), a colourless liquid, which reacts with water vapor  $(H_2O)$  to hygroscopic sulfonic acid  $(H_2SO_4)$  and hydrochloric acid (HCl) by spraying it to the air (H.Dv. 211/1, 1940; H.Dv. 211/3, 1941). Zinc and hexachloroethane (C<sub>2</sub>Cl<sub>6</sub>) filled the smoke candles. After ignition, the reaction of these two components produces toxic fumes (H.Dv. 211/2, 1939; H.Dv. 211/1, 1940). According to safety regulations issued by the German army, responsible persons operating the generators (especially smoke sprayers) were instructed to keep a minimum distance of 25 m. They were also required to wear acid-resistant suits and breathing masks for protecting against this erosive acid and the toxic fumes (H.Dv. 211/2, 1939; H.Dv. 211/1, 1940; H.Dv. 211/3, 1941). Documents from the U.S. Military Intelligence Service (1943) reported that the smoke used by the Kriegsmarine in Norway made more nose and throat irritation than that deployed at other European locations. Also, the act of pouring the liquid into the water would remove the spar varnish from fishing boats. They noted that the smoke "incapacitated men working in the vicinity, although cattle in adjoining fields apparently were not seriously affected" (U.S. Military Intelligence Service, 1943, p. 10). Local residents also reported that people had breathing difficulties (pers. Comm. Arvid Petterson). The safety instructions in the German army regulation recommended to put up the smoke generators on bare patches as the ground cover is "eaten" by the non-obscured acid and in the immediate vicinity of the accruing fog patches (H.Dv. 211/2, 1939; H. Dv. 211/1, 1940; H.Dv. 211/3, 1941). In addition, the U.S. Military Intelligence Service (1942) stated that everything on the ground that came into contact with the liquid was burned, and grass and green leaves turned yellow. These documents provide evidence that the artificial smoke negatively affected the environment in the direct vicinity of the smoke producing devices at the Kåfjord. Other information about the longer-lasting impact of the smoke on the nearby forests, however, is not available. In the sections below, we detail how we used the trees at the Kåfjord surrounding the *Tirpitz* mooring to quantify ecological impacts not obvious to contemporary observers.

#### 3. Tree-ring material from the Kåfjord, Norway

During the summers of 2016 and 2017, we collected tree-ring specimens from forests close to the Kåfjord in northern Norway, near the harbour used by the Tirpitz. Five Scots pine (Pinus sylvestris L.) stands with increasing distance to the anchor point of the Tirpitz (maximum ~7.5 km away) and one downy birch (Betula pubescens Ehrh.) stand directly at the *Tirpitz*'s anchor point were sampled at the Kåfjord (Fig. 1, Table 1). We collected two 5 mm diameter increment cores per tree at breast height ( $\sim$ 1.30 m), with a minimum replication of 25 trees at each site. The sampled stand area was rather undefined, e.g., no fixed circular plots, and varies among the sites. We randomly selected healthy looking trees without any visible natural and human disturbances or recent harvesting. Tree-ring width was measured at 0.01 mm resolution using a LINTAB measurement device and TSAPWin software (both Rinntech, Heidelberg, Germany). A total of 426 individual tree-ring width series were measured. The ring-width pattern from the individual series was cross-checked against trees from the same site and to locations nearby (Kvænangen and Porsangerfjord) to avoid measurement errors and to find locally-absent (or "missing") rings. Missing rings occur when the vascular cambium along some portion of the stem remains dormant or does not produce new cells throughout an entire growing season (Schulman, 1941). The occurrence of absent rings is one of the main reasons tree-ring series must be dated by matching relative growth patterns across many trees (Douglass, 1941; Stokes and Smiley, 1968; Fritts, 1976; Leuschner and Schweingruber, 1996; St. George, 2013). Due to their absence, missing rings cannot be measured directly, but we set them to a value of 0.01 mm for further data processing. Finally, we checked cross-dating accuracy both visually and statistically using the program COFECHA (Holmes, 1983).

Table 1

Overview of the sampled stands and characteristics of the respective chronologies. MSL = mean series length, AGR = average growth rate, Rbar = inter-series correlation, EPS = expressed population signal.

Site	Latitude [° N]	Longitude [° E]	Elevation [m asl]	Aspect	Distance to <i>Tirpitz</i> anchor point [km]	Period	MSL [a]	AGR [mm]	Rbar	EPS	# of series
Pine1	69.944	23.092	10	Ν	1.2	1848-2016	92	1.29	0.29	0.93	85
Pine2	69.919	23.111	170	NE	3.0	1808-2015	134	0.73	0.50	0.98	85
Pine3	69.915	23.114	80	S	3.5	1823-2015	92	1.06	0.31	0.94	81
Pine4	69.892	23.136	80	Ν	6.0	1653-2016	205	0.94	0.22	0.87	51
Pine5	69.884	23.163	95	W	7.5	1731-2016	150	0.97	0.32	0.93	60
Birch	69.939	23.063	140	SE	< 0.1	1882-2016	104	0.67	0.36	0.97	64

To remove age-related growth trends, we produced dimensionless ring width indices (RWI) by detrending the raw ring-width series individually using a cubic smoothing spline with a 50% frequency cut-off at 30 years (Cook and Peters, 1981). We constructed site chronologies by averaging the detrended single series using a robust mean (Mosteller and Tukey, 1977). Inter-series correlation (Rbar) and expressed population signal (EPS) statistics (Wigley et al., 1984) are used to estimate the internal coherence of each chronology (Table 1). As conservatively detrended RWI series do not allow a "real" growth change assessment, raw ring-width series were additionally transformed to basal area increment (BAI), which is better suited to represent overall tree growth (Biondi and Qeadan, 2008). Finally, we calculated the percentage growth change for each individual BAI series and each calendar year with respect to a five-year reference period preceding the 1944 artificial smoke actions.

#### 4. Effects of smoke screens on trees in northern Norway

Before the 1940s, pine trees at almost all sites near the Kåfjord featured a small number of missing rings (with at most two trees failing to form a ring in the same calendar year) (Fig. 3a). These data show that missing rings are in a way a common feature of P. sylvestris. In general, missing rings are caused by a local lack of cambial activity, meaning an interruption of new cell production, due to extremely unfavourable growth conditions (Leuschner and Schweingruber, 1996). Therefore, the rings are typically only missing along some portion of the stem, and tendentially the frequency of locally absent rings decreases with stem height (Novak et al., 2011, Wilmking et al., 2012). A range of environmental stressors can initiate the occurrence of missing rings in different tree species. These stressors include insect outbreaks (Swetnam and Lynch, 1989; Kirchhefer, 1996; Buntgen et al., 2005; Robson et al., 2015; Sanguesa-Barreda et al., 2014), volcanic eruptions (Biondi, 2001; Biondi et al., 2003), fire (Jordan, 1966), drought (Glock and Pearson, 1937; Fritts et al., 1965; Fritts, 1976; St. George et al., 2013; Novak et al., 2016) or other climatic stress such as late frost (Dittmar et al., 2006). Air pollution can also cause missing rings (Elling et al., 2009; Malik et al., 2012).

In this case, the data show that the largest cluster of absent rings in the Kåfjord forests is associated with a very particular form of anthropogenic air pollution. The use of artificial smoke in 1944 to hide the *Tirpitz* from aerial attacks left distinct imprints in the trees at the Kåfjord, reflected in a high abundance of missing rings in the following year 1945 (Fig. 3a). The high abundance in 1945 is, however, very extraordinary (cf. St. George et al., 2013) and for the first time, we can connect missing rings to chemical warfare. This specific tree damage also decreases with distance away from the *Tirpitz* anchor point. At the closest pine site (*Pine1*), 60% of the trees show a missing ring in 1945. The number of missing rings decreases in the following years, but one tree did not produce a ring for nine consecutive years. Pine2 is ~3 km away from the Tirpitz anchor point, but still 50% of the trees show a missing ring in 1945. These missing rings, however, occur only until 1947. Just 500 m further south, at Pine3, 10% of the trees have missing rings in 1945. *Pine4* is  $\sim$ 6 km away from the artificial smoke sources, and a missing ring is evident in only one single tree. Pine5, with its location in the lee of a mountain range (Skoddevarre ridge), does not show any missing ring in the 1940s.

We did not only find missing rings in pine trees. Also, 20% of the birch trees directly at the *Tirpitz* anchor point did not form a ring in 1945 (Fig. A.1). Birch, however, is known to exhibit missing rings quite often, sometimes related to late frost (Levanic and Eggertsson, 2008), but in North Scandinavia most commonly to insect attacks by foliage-feeding geometrid moths (*Epirrita autumnata* L.and *Operophtera brumata* Bkh.) (Eckstein et al., 1991; Karlsson et al., 2004; Jepsen et al., 2008; Babst et al., 2010). A high number of missing rings is also evident in other years, e.g. 1955, which is a well-known *E. autumnata* outbreak year in the region (Tenow, 1972; Eckstein et al., 1991; Kirchhefer, 1996; Karlsson et al., 2004).

The distance-dependent impact of the artificial smoke is also visible in the stand-level mean growth series (Fig. 3b). These data give insight into the severity of the tree suffering (being strongest at the closest and weakest at the farthermost site) and the duration of the recovery period. Another hint to the magnitude of the damage gives the sample replication representing the age structure at the different sites (Fig. 3c). While almost all trees at *Pine4* and *Pine5* are older than 150 years, we find an intensified germination in the 1960s and 1970s at *Pine1* and *Pine3*, implying a foregoing high tree mortality leading to new patches for

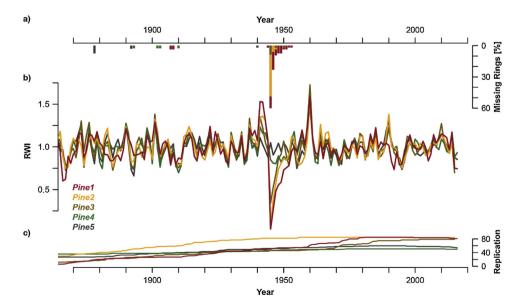
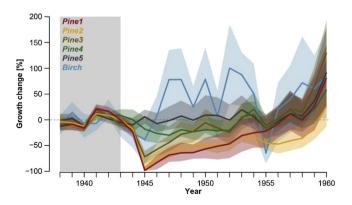


Fig. 3. Tree-ring metrics of pine growth near the Kåfjord close to the *Tirpitz* anchor point (1 = closest to 5 = furthermost). a) The percentage of trees at each site with an absent ring for each year, b) detrended ring-width index (RWI) chronologies, and c) sample replication (number of increment cores) as an estimate of the age structure at the different sites.

regeneration. These tree ages are generally underestimated, however, as cores are usually taken at breast height. This means that the trees have already a certain cambial age as they reach 1.30 m height, and the actual age is only assessable by cutting a tree at the stump. We also sampled trees randomly at each site, which might explain why *Pine2* does not show this germination pattern. A more accurate estimation of mortality and regeneration would require sampling of every tree in a pre-defined plot (Babst et al., 2014; Nehrbass-Ahles et al., 2014).

The decreasing effect of the artificial smoke on trees with increasing distance to the *Tirpitz*'s anchor point is particularly visible in the growth change pattern of the different sites (Fig. 4, note that the 25-75% quantiles of single-tree responses are represented by the shaded bands). The trees at all sites show a slight growth reduction already in 1944, with respect to the five previous years, which is the normal regional growth trend (Kirchhefer, 1998). A distinct reduction is evident, however, in the following years, especially in 1945. Trees at Pine1 show the strongest growth decline and suffered most, with almost no variance of the growth response at the stand level, represented by the narrow quantiles. The least growth reduction was 72%, and on average, the trees took 12 years for full recovery. Pine2 also experienced a strong growth decline for almost all trees (minimum decline was 49%). It even took them until 1960 until they fully recovered. As mentioned above, we assume that tree mortality was less at Pine2, which in turn corresponds to a higher stand density. A higher stand density signifies more intensive competition and, thus, results in a slower recovery of damaged trees (Juknys et al., 2003). Mean growth reduction at Pine3 is still  $\sim$ 70%, but the range of single-tree responses is already wider compared to Pine1 and Pine2. Trees already recovered in 1953. Mean growth reduction in 1945 is  $\sim$  18% at *Pine4*, and the spread of the tree responses is wider, meaning that some trees were even unaffected. Complete recovery at Pine3, however, is still only in 1953. Pine5 shows no response meaning that the artificial smoke has likely not reached this site, due to the location in the lee of the Skoddevarre mountain ridge. In contrast, the smoke affected the birch stand, which is closest to the *Tirpitz*. Among all sites, the birch stand shows the strongest growth decline in 1944. Some trees also show a strong growth reduction in 1945. This species, however, also shows the strongest spread in the magnitude and direction of single-tree responses. The entire stand already recovered fully by 1946.

The marked reduction in growth in forests close to the Kåfjord, as described by extremely high incidents of absent rings (Fig. 3a)



**Fig. 4.** Yearly growth change of trees in pine and birch stands near the *Tirpitz*'s anchor point. Pine stands are numbered by increasing distance from the Kåfjord. For each stand, the growth change represents the increase or decrease in basal area increment relative to a five-year reference period (the grey band) preceding the 1944 artificial smoke actions. The solid lines show the mean growth change by stand while the shaded bands describe the quantile range of single trees at that location.

and declines in basal area increment (Fig. 4), is due to the negative effects of the artificial smoke on the forest canopy and foliage. Documents from the 19<sup>th</sup> century already reported that smoke can damage the needles and leaves of trees (Stöckhardt, 1871; von Schroeder and Reuss, 1883). Haselhoff and Lindau (1903) also investigated experimentally the effect of sulfonic acid and hydrochloric acid on trees: if plants get in contact with the corresponding smoke, the water circulation in the leaves is disturbed leading to dehydration and bleaching of the chlorophyll (von Schroeder and Reuss, 1883; Haselhoff and Lindau, 1903). More recent studies have also shown that hexachloroethane obscurant (and other fog oil) injures the foliage of trees and leads to chlorosis (Sadusky et al., 1993; Getz et al., 1996). Based on the geographic pattern of the trees' response, it seems likely that trees at Pine1 to Pine3 were severely defoliated, leading to lower photosynthesis rates and consequently restricted growth. Similarly, the trees at *Pine4* were moderately defoliated and less affected by growth reductions as the radial increment of pines is directly related to the percentage crown defoliation (Juknys et al., 2003). For birch, Hoogesteger and Karlsson (1992) found that defoliation leads to growth reduction, but with higher differences among individual trees, which is in agreement with results from this study.

Defoliation is a dramatic event, in particular for evergreen tree species because these species store larger quantities of nutrients and carbon in their needles compared with that stored in the leaves of deciduous species (Krause and Raffa, 1996). That broadleaved trees were less sensitive to the artificial smoke than were conifers is also apparent. This differential sensitivity is related to the foliation longevity of the different tree species. While birch is a deciduous tree species and produces new leaves every year, the memory effects of the defoliation caused by the artificial smoke are less pronounced, leading to a rather quick recovery in 1946. In contrast, needle longevity of the evergreen pine trees is expected to be 6 to 12 years in northern boreal forests (Jalkanen et al., 1995; Pensa and Jalkanen, 2005). This means that the trees first have to substitute the damaged needles, so that pine stands needed up to 12 years until complete recovery. Compared with other disturbance regimes, this recovery period is extraordinarily long. For instance, other studies showed that *P. sylvestris* recovers from drought within 3-4 years (Eilmann and Rigling, 2012). In addition, through pathogen induced defoliation recovery took a maximum of 5 years (for the individuals, which survived) (Olivia et al., 2016). This means that the unusual form of anthropogenic disturbance at the Kåfjord was, at least for nearby forests, more destructive than would be expected from other natural disturbance factors.

#### 5. Summary and conclusions: tree rings in "warfare ecology"

Analysis of more than 200 trees collected in 2016 and 2017 from forests surrounding the Kåfjord in northern Norway permit answers to the research questions posed in this paper. (1) The artificial smoke used to hide the *Tirpitz* from aerial attacks caused widespread defoliation resulting in a strong and unusual growth decline in 1945. (2) This damage extended up to 4 km away from the *Tirpitz* and, in the most extreme case, tree growth was interrupted for up to 9 years. Overall, growth decline was very long-lasting and on stand level it took up to 15 years for full recovery, which is not comparable to other natural disturbance factors. (3) Pine forests were more severely and longer affected than birch forest due to the differing foliation longevity of these two tree species.

Hupy (2008) outlined three categories of environmental disturbance through warfare: i) environmental disturbance and destruction from weaponry; ii) direct consumption of resources, such as timber, water and food to support armies; iii) indirect

consumption of resources by military industrial complexes that supply the war effort. These categories, however, do not include the effects of warfare identified at the Kåfjord. The type of disturbance at the Kåfjord may better reflect a collateral damage of the environment just through the presence of the battleship *Tirpitz*.

Results of the tree-ring analysis from the Kåfjord also suggest insights in the application of dendrochronology on documenting the impacts of war on forest ecosystems. Trees are an excellent archive as they record environmental changes and impacts in a high temporal resolution by forming an annual distinct ring each year. Dendrochronology, or tree-ring analysis, is applicable to a variety of climatological and ecological research questions, including, inter alia, climate reconstructions, growth responses to extreme climatic events, fire history, insect outbreaks, and air pollution. Expanding the disciplinary boundaries of tree-ring research (Büntgen, 2019), this study is the first, to our knowledge, where tree rings documented a military conflict. Although the military conflict in the Kåfjord was relatively small (only the presence of a single battleship with some convoying ships) and brief (only a few air attacks within less than a year), it still left clear evidence under the bark of the trees. Because preservation is so long, and because war generated artificial smoke widely, similar imprints may be visible in other forests close to WWII military battles. This study, therefore, suggests the potential of this nascent sub-field of dendrochronology to evaluate the effects of wartime across forests in Europe and elsewhere.

#### **Declaration of interest**

None.

#### Acknowledgements

We thank Markus Kochbeck, Philip Bergforth, Ben Lehmann, Bianca Müller, Johannes Neumann and Marcus Schwarz for help with laboratory work and several geography students from the Johannes Gutenberg University Mainz who supported fieldwork during the North Scandinavia Excursions in summer 2016 and 2017. We also thank the forest owner Finnmarkseiendom for sampling permission as well as historian Arvid Petterson, Lakselv, for proving the first lead towards *Tirpitz* and artificial smoke in Kåfjord. This work was supported by the German Science Foundation [SCHO 1274/13-1, Inst 247/665-1 FUGG, ES 161/9-1, HA 8048/1-1] and the Alexander von Humboldt Foundation.

#### Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ancene.2019.100212.

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