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Heat and Drought Induced Impacts on the German Railway Network

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Abstract

In view of the predicted climate change towards drier and hotter summers in Germany, heat- and drought-related disturbances in railway traffic are likely to increase in the next decades. This paper focuses on vegetation-related disturbances in the immediate vicinity of the German railway network, namely embankment fires and drought-induced tree falls. First, the spatiotemporal occurrence of the two processes is presented. Based on a Maximum Entropy model, a Germany-wide risk indication map for embankment fires along the rail network was developed. A GIS tool for determining tree fall risk is presented that incorporates the parameter tree vitality, allowing the detection of tree stands weakened due to adverse climate conditions. The maps and tools can help make the German rail network more resilient to heat- and drought-related disturbances and thus better adapted to climate change.

Keywords: resilience to extreme weather events; risk mitigation; railway transport; risk map; embankment fire; tree fall

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1. The impact of heat and drought on railway operation – an overview

Extreme weather events, such as floods, storms or extreme heat, have manifold impacts on transport services. Due to its low ability to compensate hazard related disturbances, the railway transport system is especially vulnerable (Blackwood et al. 2022). According to the European Railway Agency (ERA), extreme heat is one of the major weather- related threats to railway traffic infrastructure and service causing a variety of direct and indirect impacts (Villalba Sanchis et al. 2020). Possible direct high temperature effects on railway infrastructure are thermal expansion

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in structures (e.g., buckling of rails at temperatures above 25 °C) and electronic malfunctions of trackside objects (Palin et al. 2021; ProRail 2019a). In particular, high heat (from a temperature of 32 °C) leads to increased disruptions of the rail infrastructure in Germany (Edenhofer and Hoffmann 2021), and Greenham et al. (2020) recognized clear trends and relationships between delays and high temperatures in the London Underground rail network. Nguyen et al. (2012) reported disruptive rail buckling in Melbourne, Australia in 2009 caused by extreme heat. More recently, in July 2019, trains were subject to speed reduction in the UK, and in the Netherlands extra track inspections were conducted (ProRail 2019b) to reduce the potential for derailments due to buckling risk (Palin et al. 2021). Furthermore, overhead power line integrity can be affected by heat through excessive sag (Palin et al. 2021).

Additionally, natural hazards, which are associated with high temperatures, such as heatwaves, drought and wildfires or embankment fires in the closer surrounding of the railway lines, can have direct effects on rail traffic and infrastructure. A precipitation deficit in combination with high temperatures or a heatwave can cause drought conditions, triggering the drying of soils, shrinkage cracking and land sliding. Accordingly, possible effects of drought on railway infrastructure are infrastructure slope failure, track misalignment, and misalignment of poles supporting overhead lines (Palin et al. 2021). Furthermore, heat and drought can cause indirect or subsequent temporally delayed effects on rail traffic. The vitality of vegetation can be decreased by heat and drought. In a long term, this makes trees more vulnerable to storm throw and snow load and thus increase the risk of rails traffic infrastructure and operation failure.

Current climate change is connected to temperature increase in most parts of the world (Masson-Delmotte et al. 2021). The duration, magnitude, scale, and frequency of weather and climate extremes are projected to change, resulting in unprecedented extremes (Seneviratne et al. 2012). Hence, the observed “extreme” weather of today could become the "normal" weather of tomorrow (Nolte 2011). Adapting railway infrastructure to climate change is critical to ensure continued operations under future climatic conditions, but it is a major challenge. Many of the individual structures along railway lines, such as bridges, tunnels and earthworks, are more than 150 years old and were thus built before the advent of modern design and construction standards (Palin et al. 2021). In addition, rail infrastructure is expected to operate for more than 50 years, making it necessary to integrate climate change adaptation into long-term railway planning, design, and management processes (ClimateADAPT 2021).

While most of the studies dealing with heat-related impacts on railways focus on the railway infrastructure itself, the influence of heat on vegetation close to railway lines is often disregarded. Especially for the case of embankment fires, international literature shows only very limited interest to the topic. Arndt (2006) investigated the issue of embankment fires for the Austrian railway routes. Detecting a high susceptibility of selected railway routes, she concluded in recommendations for bio-engineering measures as well as mechanical measures to reduce embankment fire risk. To adapt vegetation management is a valuable tool to face the challenges of climate change, and the implementation of nature-based solution in railway maintenance, where e.g., creating green corridors or adapted species selection, is highly encouraged (Blackwood et al. 2022). On the one side, vegetation has a cooling effect on the surrounding and can hence reduce peak temperature values (Blackwood et al. 2022; Marteaux 2016). On the other side, impacts caused by vegetation are a major threat for rail traffic. Accordingly, studies that address the interaction between trackside vegetation and railway operations and the associated hazards are of need.

This work focuses on two different drought and heat related impacts in the immediate vicinity of the German railway network that are related to trackside vegetation: embankment fires and drought related reduction of tree vitality fostering a higher risk of storm throw. First, an overview of the current and future situation of heat-prone areas in Germany is given to identify regions where the railway network is most affected. Secondly, in Chapter 3, triggering factors of embankment fires, an overview of the spatio-temporal distribution of past embankment fires, and a Germany-wide risk indication map of embankment fires along the railway network, are presented. Thirdly, in Chapter 4, the focus is on the effects of heat and drought on trackside vegetation and their leverage effect on natural hazards, such as storm throw. Here, a GIS-tool that integrates tree vitality as a parameter to determine tree fall in nationwide hazard indication maps is presented. Finally, the paper ends with recommendations for an adapted vegetation management.

2. Heat-prone parts of the German railway network

Considering regional climate models, Germany will likely experience an increase of climate extreme events in the future, especially more intense heat waves and drought periods, heavy rainfall events and violent storms (Brasseur et al. 2017). Figure 1 shows the spatial distribution of the number of days with maximum temperatures ≥ 25°C for Germany. Over all of Germany the number of days ranges between 0-60 days per year in the reference period 1971-2000. Regional differences arise with a lower number of summer days in coastal and mountainous areas and with a higher number of summer days along the Upper Rhine and in South of the Federal state of Brandenburg. The climate projections show increasing summer conditions in the future decades in wide parts of Germany, especially along the Upper Rhine with up to 100 days with maximum temperatures above 25°C per year. Despite model uncertainties (likely range between 15th and 85th percentile), large parts of the country will experience 40-60 summer days in the forthcoming decades 2031-2060. Regional differences remain stable with larger temperature increases in the southern and eastern parts of Germany. Important TEN-T corridors traverse the most heat-prone areas of Germany, particularly noteworthy is the Rhine-Alpine corridor. From a national perspective, significant transport hubs are located in the particularly warm regions (Berlin, Frankfurt, Cologne, Stuttgart).

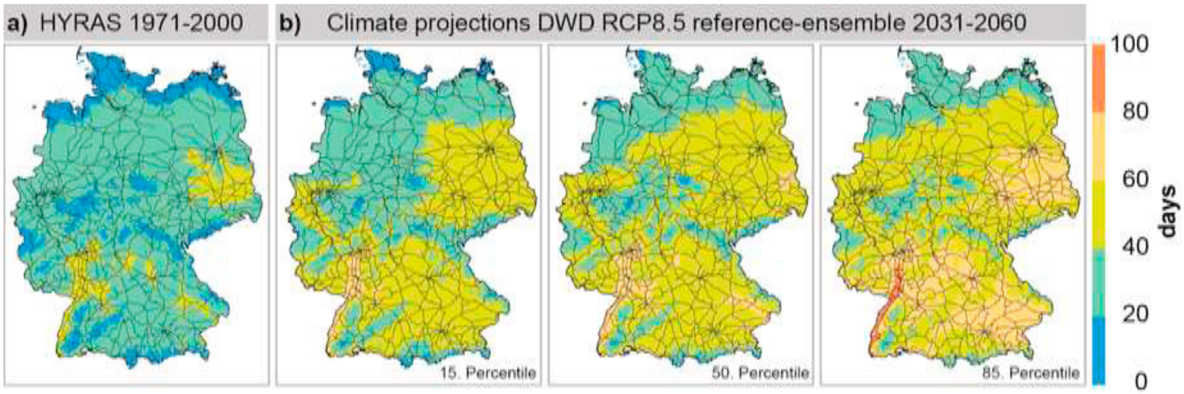

Fig. 1. Number of days maximum temperatures ≥ 25°C (summer days) today and in the upcoming decades. Current and future temperatures were derived from (a) the gridded observational dataset HYRAS for the reference period 1971-2000 and (b) the German Meteorological Service's (DWD) climate model reference-ensemble for the period 2031-260 under greenhouse gas emission scenario RCP 8.5 (21 ensemble members) using different percentile thresholds to account for model uncertainties (Krähenmann et al. 2021; Razafimaharo et al. 2020). The black lines represent the German railway network.

3. Embankment fires

Embankment fires along railway infrastructure along railway infrastructure are a major threat, especially during summer months, and regularly lead to delay and cancellation of rail traffic services. Between 2017-2020, 1100 disruptions in the operating sequence through embankment fires were reported by the German railroad company „Deutsche Bahn", on average 278 disruptions through fires per year (Fig. 2). The regional distribution shows a concentration of disruptions through embankment fires in urban areas such as the city of Berlin, the Rhine-Main and the Rhine-Ruhr area. The temporal occurrence shows a clear seasonal pattern, with a peak of events in July (2019: 90; 2018: 74, 2020: 70) and over 55% of all events occurring during summer (June, July and August). Particularly outstanding is the year 2018, in which 457 disruptions through embankment fires were recorded. The summer of 2018 was one of the hottest and driest summers reported in Germany, leading to a visible heat- and drought-induced disturbances balance in installations of the roadway and the control and safety technology (Meßenzehl 2019). With regard to the predicted climate change towards drier and hotter summers in Germany (Brasseur et al. 2017), the risk for embankment fire events is likely going to increase within the next decades.

In general, fire risk assessment distinguishes between the risk of ignition and the extent of fire after ignition, the spread potential. Meteorological parameters such as precipitation, humidity, cloud cover, surface and air temperature, wind direction and speed (San-Miguel-Ayanz et al. 2018; Szpakowski and Jensen 2019), as well as vegetation-related characteristics influence both: ignition and spread potential (Toukiloglou et al. 2013). Prolonged dry periods leading to desiccation of soils and vegetation are generally considered to promote fire. Ignition potential related vegetation characteristics are often described in so-called fuel maps, such as those developed for the Mediterranean region (Toukiloglou et al. 2013). Here, topographic parameters such as slope and exposure foster the risk of ignition due to a longer duration and increased intensity of solar radiation (Szpawkowski and Jensen 2019). The spread potential is mainly driven by topography, as fires can spread faster in hilly terrain.

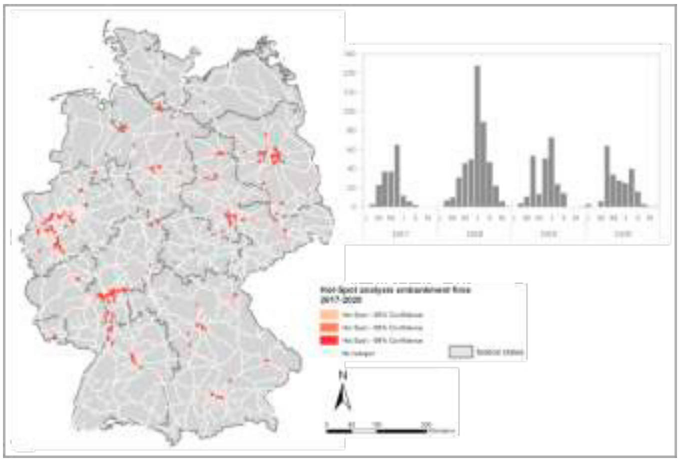

Fig. 2. Spatial and temporal distribution of disruptions in the operating sequence due to embankment fires along the German railway network between 2017 and 2020.

While there are numerous scientific studies on wildfires (e.g., Bowman et al. 2020 and references therein), studies on embankment fires are very limited. The specific structures of trackside vegetation, the rail infrastructure related modification of the landscape and anthropogenic usages along transportation routes differ strongly from forest habitats. Additionally, unlike other natural hazards such as floods or mass movements, embankment fires can be triggered by train operation itself, making embankment fires more likely to occur on lines with high traffic volume, especially freight traffic. For example, sparking during braking, must also be taken into account, and sparking of power lines and overhead power lines can ignite embankment fires (BS 2020; BV 2018; FFM 2013; OZ 2012; Railwatcher 2019). Further anthropogenic factors include litter in the embankment area, especially cigarettes and broken glass, as well as private fires at social gathering places or in allotments, which are often located near tracks in Germany (BS 2020; BV 2018; OZ 2012). Hence, the transferability of factors driving wildfire risk to embankment fires might be limited.

Based on incident reports, local exposure and hazard information, Maximum Entropy models were developed to identify major drivers of embankment fire risk and to develop an embankment fire risk map for the Germany-wide railway network (Frick et al. in prep.). The Maximum Entropy method was developed by Jaynes (1957) to allow statistical predictions or inferences from incomplete information (please see detailed explanation in Phillips et al. 2006). One of the advantages is that Maximum Entropy models are generally suitable for providing meaningful results even with few reference points. This is especially important, since the number of reported impacts had to be reduced to 47 due to imprecise spatial location of most reports. Out of the 47 events with precise xy- information, 33 of which were used to train the model, the other 14 were used to test the model. To train the algorithm for impact prediction, a total of 11 different parameters from the categories railway (distance to curves and operating points; distance to settlement areas), meteorology (surface temperature; summer mean Soil Moisture Index of topsoil; wind speed), topography (slope orientation; aspect; altitude; angular difference slope orientation to track orientation) and vegetation (FuelMap classification) were used. The results highlight the importance of local orography such as slope gradient and orientation, hydro-meteorological conditions as well as distance to urban settlements for the embankment fire risk potential. Depending on the above listed parameters, a 5 m gridded, German-wide risk map of embankment fires along the railway network was developed, where every grid cell indicates a risk potential from low (0) to high (1).

Figure 3 shows the overview map for estimating the risk of embankment fires along the Germany-wide railway network. For this aggregated representation, the rail network was divided into 5 km sections and buffered by 50 m. Within the area, every 5 m grid cell with a hazard potential of more than 0.5 of the nation-wide processed detailed hazard assessments were then added up. The aggregated map below shows the sum of grid cells with a hazard potential of more than 0.5 in hectares per 5 km track section. Germany-wide, about 9 % of the area is endangered, i.e. has a hazard potential > 0.5. On a regional scale, densely populated areas such as the city of Berlin, the Rhine-Ruhr area and the Rhine-Main area present current hot spot regions. As shown in Fig. 1, these regions correspond to the present and future particularly warm areas of Germany.

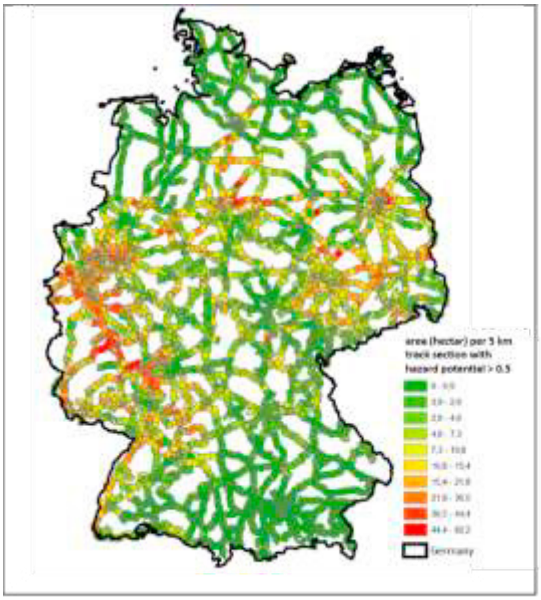

Fig. 3. Embankment fire risk map for the German railway network based on a Maximum Entropy model with several parameters from the categories railway, meteorology, topography and vegetation. The map shows the sum of grid cells with a hazard potential of more than 0.5 hectares per 5 km track section.

4. The effects of heat and drought on trackside vegetation

Trackside vegetation has several positive effects on the track environment, both from an ecological point of view and as a measure against natural hazards. According to Blackwood et al. (2022) vegetation helps managing surface water runoff, improve water quality and air quality by capturing or acting as a barrier to the dispersal of pollutants produced by vehicles (Davies and Hockridge 2014), stabilise embankments (Greenwood et al. 2004), and provide resilience during heatwaves (Marteaux 2016). On the other hand, tree fall on railway tracks or overhead lines rank among the most common causes for disruptions of natural origin, leading to train cancellations and delays or directly damaging trains and people (Meßenzehl 2019).

Disturbances of the operation sequence through tree fall events affecting the railway network occur much more frequently than through embankment fires with a total number of 10.773 between 2017 and 2020, on average 2.693 disturbances per year. Typically, tree fall events are caused by storms, which mainly occur between October and March in Germany (Gardiner et al. 2010). Hence, the highest number of disturbances is observed in months with large storm events, e.g. in October 2017 or February 2020. Tree fall events occurring in the summer months (June, July and August) can be attributed to heavy rainfall events in combination with thunderstorms, which are often accompanied by violent squalls. For instance, in late summer 2018 heavy thunderstorms with torrential rain and localized squalls caused disruptions due to tree falls, track undermining and lightning strikes (Meßenzehl 2019). The regional distribution shows a more diverse pattern as for embankment fires (Fig. 2). In addition to urban areas, rail lines in predominantly forested middle mountain regions and in northern Germany, the areas most susceptible to wind, are most affected by tree falls.

Beside meteorological conditions, tree vitality is an important parameter determining the risk of tree fall, as trees in poor health are more susceptible to falling. In the context of climate change, many tree species suffer from longer and more intense drought periods, leading to higher tree mortality rates worldwide (Allen et al. 2010). It is therefore necessary to implement information on tree vitality in vegetation management tools. An example is given in Szymczak et al. (2022) who developed a user-friendly GIS-tool, allowing an up-to-date and area-wide monitoring of single trees along railway lines and further infrastructural elements. Beside the parameters tree height and distance to the railway lines, important on site parameters describing meteorological and topographic conditions as well as tree characteristics were implemented in the tool. Having a special focus on drought and heat induced vegetation stress, the parameter tree vitality was also integrated. Tree vitality information was taken from the ForestWatch-DE portal, a nationwide vitality grid developed by Luftbild Umwelt Planung GmbH (LUP 2019), using a methodology based on the Disease Water Stress Index according to Galvão et al. (2005) and is based on multitemporal Sentinel 2 data of the years 2017, 2018 and 2020.

In a case study, tree detection and monitoring of their vitality in the year 2020 along rail lines was implemented for two federal states in Germany, Northrhine-Westphalia (NRW) and Thuringia (TH) (Fig. 4). In NRW, a total number of 2.399.990 trees was detected in the close vicinity of the railway network, in TH 488.169. The classification into deciduous and coniferous trees shows a slightly higher proportion of deciduous trees in both federal states (53 % and 56 %, respectively). However, looking at vitality losses in 2020, there are significant differences between the two states with larger percentage of trees in both classes showing vitality losses in TH compared to NRW (Fig. 4). While in NRW more conifers are affected than deciduous trees, the situation in TH is exactly the opposite. Because of the data availability, the reference year in NRW is 2018 and in TH 2017. Although a direct comparison of the vitality losses of the two states is only possible to a limited extent and very likely biased due to the hot summer of 2018, these results show that the vitality status of trees near railway lines is an important and time-sensitive parameter. It may become even more important as climate change increases heat and drought stress. We therefore recommend that tree vitality should be taken into account when assessing the risk of tree fall and selecting suitable tree species for use as trackside vegetation. However, it should be pointed out here that a loss of vitality does not automatically lead to a tree fall, but the health status of a tree is only one of many parameters that influence the risk of a tree being susceptible to windthrow.

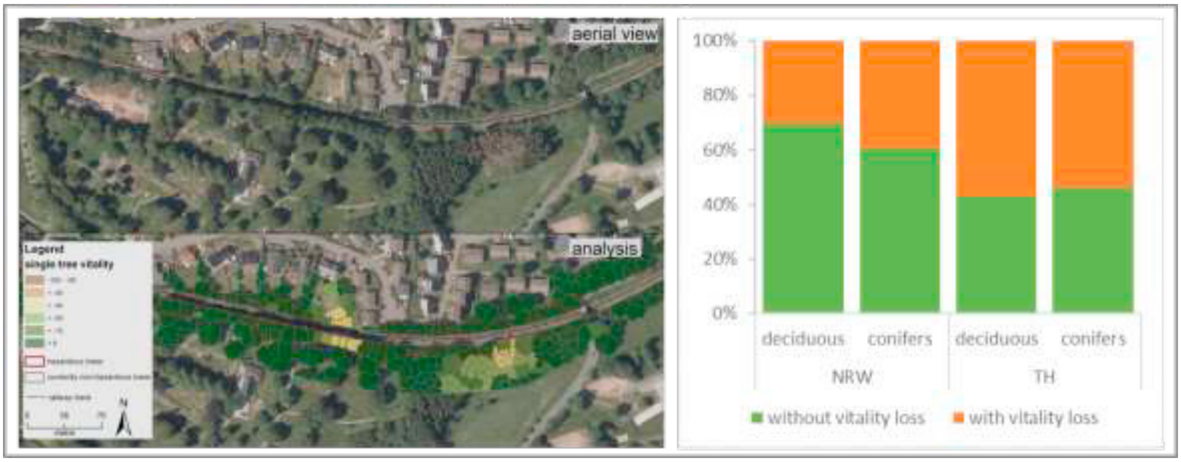

Fig. 4. An example of monitoring tree vitality along the railway network of Northrine-Westphalia (left), and percentage of trees with and without vitality losses in 2020 in the close vicinity of the railway network in the federal states Northrhine-Westphalia (NRW) and Thuringia (TH), classified into deciduous trees and conifers (right). The vitality loss for 2020 is calculated as the difference to a reference year (2017 for NRW, 2018 for TH).

5. Conclusions

The tools presented (risk map and GIS-tool) can help to make the German railway system more resilient to heat- and drought-related disturbances caused by trackside vegetation and thus better adapted to current climate change. Furthermore, the analyses enable recommendations for action regarding vegetation management as an important part of a proactive natural hazard management. A first step is to create risk maps for various natural hazards to identify the regions most at risk. Promoting drought-tolerant and low-flammability species in these hot spot areas is a valuable contribution to increasing the resilience of rail transport to embankment fires and tree falls. We therefore recommend that parameters describing vitality and drought tolerance be incorporated into existing vegetation management and monitoring systems. However, selecting appropriate species for trackside vegetation is a challenging task because other parameters such as storm resistance, stability, positive influence on slope stability and maintenance requirements must be considered as well. It is equally questionable whether the research results to drought tolerance obtained in large-scale forest areas can be transferred one-to-one to tree and forest areas near railways. Since the railway environment is characterized by a particular microclimate and special site conditions, further research in this specific environment is necessary.

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