Closing the Gap in German Loss and Damage Data. The Importance of Heat- and Drought-related Extreme Events

Summary of Results from the Research Project 'Estimation of Costs Resulting from Climate Change in Germany'

Research project:
Estimation of Costs Resulting from Climate Change in Germany

On behalf of:
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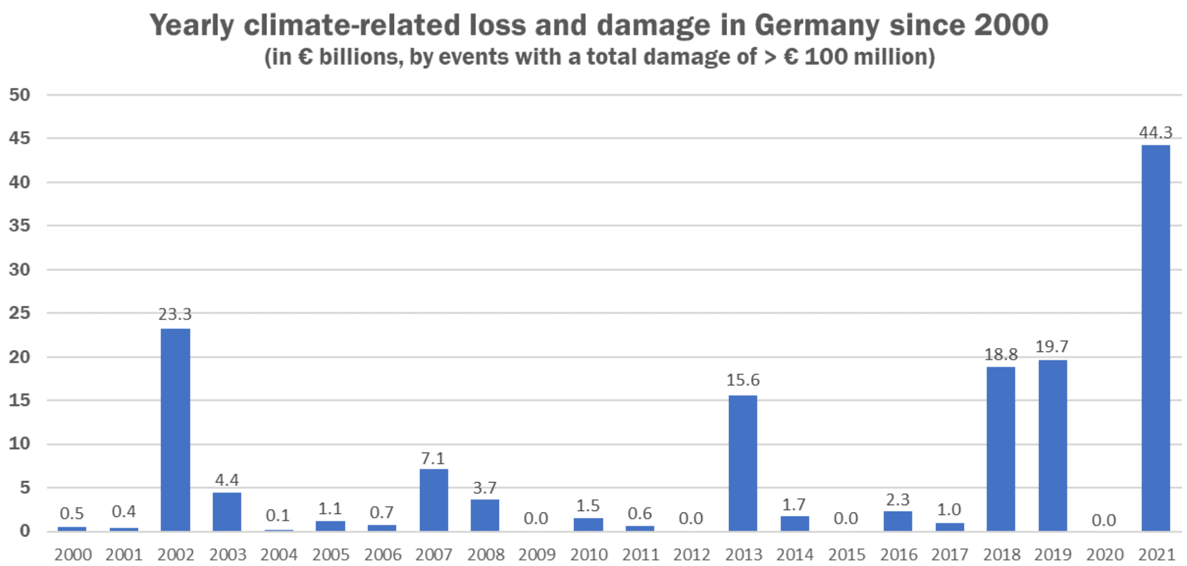
1 Introduction

Weather- and climate-related events such as floods, heavy rain, heat, and drought cause substantial loss and damage and high numbers of fatalities in Europe already today. The European Environment Agency (EEA) reports that between 1980 and 2020, total economic losses from weather- and climate-related events amounted between €450 and 520 billion (adjusted to inflation for 2020) in the 32 EEA member countries (EEA, 2022). For Germany, the reported economic losses range between €107 and 111 billion, or around €2.7 billion per year on average. In fact, figures by Trenczek et al. (2022) suggest even higher economic losses. The authors estimate costs of at least €145 billion resulting from weather- and climate-related events in the period between 2000 and 2021 alone. This implies an almost three-fold in the yearly averaged economic losses in Germany, compared to EEA numbers.

Figure 1: Yearly climate-related loss and damage in Germany since 2000



Source: own elaboration. Data for the years until 2017 are taken from various disaster databases (EM-DAT, HANZE, etc.) and were adjusted to inflation for the year 2021.

A key factor that drives this discrepancy is the fact that Trenczek et al. (2022) include estimates on heat- and drought-related loss and damage that occurred in the years 2018 and 2019. With a total cost of about €35 billion, the losses within the two-year period reign among the costliest weather- and climate-related events in Germany since 2000, as shown in Figure 1. In the EEA database which technically covers data on storms, floods, mass movements, heatwaves, cold waves, droughts, and forest fires, heat- and drought-related loss and damage is not systematically represented. The same holds for most other databases containing information on disasters, natural hazards or climate events.[1]

Motivated by this underrepresentation, this paper provides a comprehensive picture on the underlying economic losses and damages that occurred as a result of the droughts and heatwaves in the years 2018 and 2019 in Germany. While estimates on fatalities due to heatwaves have been regularly published (Watts et al., 2018; an der Heiden et al., 2020; Axnick, 2021; Winklmayr et al., 2022), estimates of heat- and drought-related loss and damage are sparse, fragmented and exist rather in the form of ad-hoc evaluation by experts. In this paper, we collect information on a set of indicators to record loss and damage in the agricultural (€7.8 billion), forestry (€17.8 billion) and the industrial sector (€9.2 billion). The results thereby showcase large remaining vulnerabilities in all three sectors.

This study contributes to the literature on loss and damage data of weather- and climate-related events in several ways.

First, it addresses a blind spot. A comprehensive examination on heat- and drought-related loss and damage in Germany is currently missing. What existing information suggests, however, is that these loss and damages are substantial (Möhring et al., 2021). Moreover, gauging these losses and damages is not only relevant given previous and recent heatwaves and droughts (e.g., 2003, 2006, 2011, 2020-2022). It becomes even more important considering the clear evidence on the increased probability and intensity of droughts and heatwaves in Germany and Europe caused by climate change (World Weather Attribution, 2018; Vautard et al., 2019).

Second, this study lays out a framework to quantify the losses and damages from heatwaves and droughts utilizing publicly available information for Germany. Quantifying these economic losses is challenging. One problem is poor coverage of insurance data. Most estimates on the economic costs of weather- and climate-related disasters build heavily on insurance information. However, currently, only as few of 2% of the agricultural area in Germany is insured against drought. Moreover, impact chains due to heatwaves and droughts are complex, manyfold, hidden, and hard to quantify as well as to monetize. For instance, the Climate Risk and Vulnerability Analysis for Germany (Kahlenborn et al., 2021) considers 102 impacts due to heatwaves and droughts. This study scrutinizes what impacts can be quantified and expressed in monetary terms given the currently available data and methods.

Third, this paper contributes to the literature by estimating not only direct but also gauging estimates for the occurring indirect costs. Typically, existing databases only cover direct costs of weather- or climate-related events. By employing indirect to direct cost ratios identified throughout existing literature, e.g., Sieg et al. (2019), this paper presents an approach to also estimate the indirect effects of the direct costs along value chains.

Fourth, by comparing the economic losses from heatwaves and droughts to the flooding catastrophe in July 2021, the study reveals similarities and differences regarding the magnitude as well as vulnerabilities. Thus, this study helps to inform policy making, particularly in the context of the German climate adaption strategy.

Chapter 2 of this paper provides background information on the availability of loss and damage data from weather- and climate-related events including their classification. Chapter 3 describes the severity of the heatwaves and droughts in 2018/2019 and its quantifiable impacts on different sectors. Chapter 4 presents the employed method to quantify the loss and damage of the heatwaves and droughts in 2018/2019 in Germany. Chapter 5 displays the results of the estimates and compares them to the losses of the floods in July 2021. Chapter 6 concludes the study, states its limitations, and describes the need for future research.

[1] A second important factor is that the EEA figures do not include the flooding catastrophe in July 2021 caused by the depression "Bernd". The flood caused 183 deaths and widespread destruction, amounting to estimated economic losses of €40 billion across Germany, particularly in the Ahr valley (Mohr et al., 2022; Trenczek et al., 2021).

2 Availability of loss and damage data from weather- and climate-related events in Germany

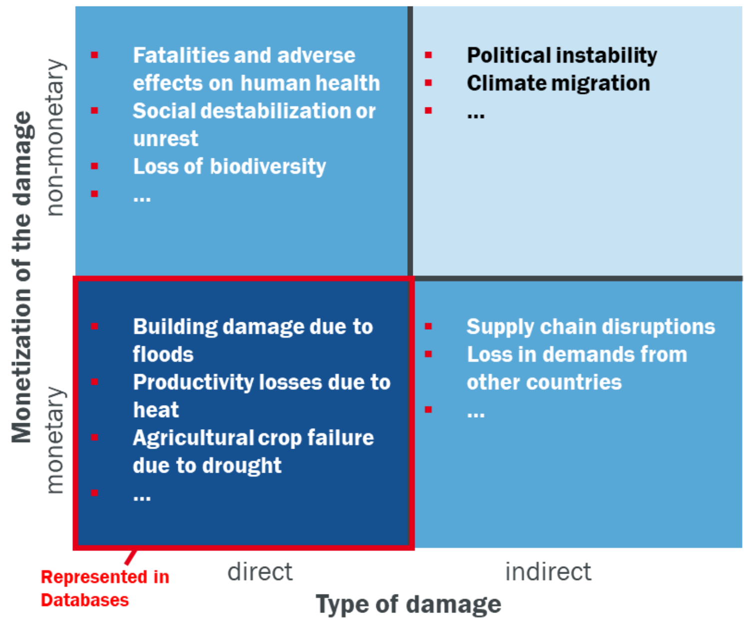
To date, no transparent and statistics-based official overview on economic losses from weather- and climate-related events in Germany exists. Instead, only some institutions and private companies record information of loss and damages from past weather- and climate-related events in databases. For instance, the EEA publishes yearly information on economic losses and fatalities for the period from 1980 onwards, covering all 32 EEA member countries. The EEA itself however relies on data from the CATDAT database of RiskLayer as well as the NatCatSERVICE database of Munich Re which are not publicly available. Other relevant databases include the Risk Data Hub of the EU Disaster Risk Management Knowledge Centre, the Emergency Events Database (EM-DAT) of the Centre for Research on the Epidemiology of Disasters (CRED) or the databases HOWAS21 and HANZE by the GFZ Potsdam and TU Delft, respectively. Across the different mentioned databases, more than 600 individual events have been recorded for Germany since the year 2000 alone. In addition, the German Insurance Association (GDV) publishes information on insured and economic losses in its annual natural hazards report.

2.1 Classification of different types of loss and damage

Still, data gaps in loss and damage data exist. Available databases only track a fraction of possible loss and damage information, specifically the directly occurring events which can be recorded and are monetizable by the means of a valid indicator. However, since the impacts of weather- and climate-related events are manifold and complex, the total picture of the loss and damages goes beyond that classification. Conceptually, loss and damage can be organized into direct and indirect damages on the one hand, and monetizable and non-monetizable damages on the other hand (see also Figure 2). For example, health damages, political instabilities, or supply chain disruptions either are classified as non-monetizable or indirect damages and are hence not included in existing databases.

However, a closer look at existing databases also reveals several blind spots within the classification of monetizable and direct losses and damages. Specifically, while storms, hail and floods are covered comprehensively, monetary estimates on heat- and drought-related loss and damage are lacking. Only one of the consolidated 600 event entries in existing databases since 2000 represents a monetary loss and

Figure 2: Systematization of climate-related loss and damages



Own illustration based on Hirschfeld et al. (2021)

damages estimate due to a heat-related event.[2] Not one entry refers to a drought-related event. A major reason for the underrepresentation of heat- and drought-related losses and damages is that recorded loss and damages heavily draw on information from insurance policies, which are highly unevenly distributed across hazard types (Gesamtverband der Deutschen Versicherungswirtschaft e.V., 2020). Looking at insurance policies for arable land, more than 75% of the area in Germany is insured against hail, while less than 2% is insured against drought-related loss and damage [3].

Aside from databases, official reports and academic research papers provide information on loss and damage from weather- and climate-related events in Germany. There is, however, only sparse information on the monetary cost of past heat- or drought-related events in Germany even in these sources. For instance, after reviewing the literature, Bubeck and Kreibich (2011) point out that contrary to other past extreme events in Germany, such as the floodings in 2002, costs from droughts are usually not explicitly modelled. Instead estimates rely on ad-hoc valuations by authorities, experts or persons directly concerned.

2.2 A first look into bottom-up estimates of data gaps

Gömann et al. (2015) provide an exception for the case of heat- and drought-related losses of wheat in the year 2003. Collecting information from the literature, expert interviews, and primary data from 11,500 representative businesses, the authors examine the impacts of extreme events on wheat yields for the period 1995 to 2013 using a multiple regression analysis approach. Assuming a constant price, the estimates of Gömann et al. (2015) suggest costs from reduced wheat yields in the year 2003 of €546 million.[4] The authors show that 90% of the reduced yields in the year 2003 can be accounted for by heat and drought stress. Based on an average yield decrease of 8 decitons per hectare, a cultivated area of approximately 3 million hectares and a producer price of €20 per decitons, the estimated costs of heat and drought stress add up to €480 million.[5] For other crops, detailed information required to estimate the impact of past periods with heat and drought stress based on regression approaches are not available. A more pragmatic approach to estimate costs is to compare the yield in periods with heat and drought stress to average yields in the previous period. This approach however comes with the problem that price effects cannot be clearly separated from quantity effects. Moreover, compensating effects may occur. Also drawing on the data of Gömann et al. (2015), the GDV published a special issue on loss and damage due to heat and drought stress in the agricultural sector (Gesamtverband der Deutschen Versicherungswirtschaft e.V., 2016). According to the authors, droughts in Germany caused average annual crop damage of around €275 million between 1990 and 2013, accounting for more than half of the damage recorded by GDV in agriculture during this period. Two years with particularly high numbers stand out. For the year 1992, losses of €2.1 billion (in 2013 prices) and for the year 2003 losses of €1.6 billion were registered. Notable losses of over €300 million were also recorded for the years 2006 and 2011.

Besides the agricultural sector, the forestry sector particularly suffers from drought stress. Based on the volume of damaged timber in the years 2018 to 2020 and supplementary information, Möhring et al. (2021) calculate in detail the operational damage costs in forestry due to reduced

[2] For the year 2003 the EM-DAT database records a monetary loss and damage estimate due to heatwaves of €1.6 billion, consistent with the information provided by the Gesamtverband der Deutschen Versicherungswirtschaft e.V. (GDV) (2016).

[3] Estimates vary ranging from 0,02% coverage via multi-hazard insurance policies (Scheele, 2018) to less than 2% according to estimates from the German farmers association.

[4] In the period 1995 to 2003, the average sector yield amounted to approx. 74 decitons per hectare. In the year 2003, the yield amounted to 12.5% below the average yield. The assumptions of a cultivated area of approx. 3 million hectares and a producer price of €20 per dt remain. For further information see table 3.3. and remarks in Gömann et al. (2015).

[5] The assumption of an average yield decreases by 8 dt per hectare is derived from a (rounded) summation of the impact coefficients for the variables “days above 25°C”, “days without rain 10 days before and 20 days after beginning of vegetation” as well as “repeating drought in the vegetation period in the year 2003” (Gömann et al., 2015).

revenues, additional costs, losses due to immaturity at the time of cutting and losses in value growth. In total, the authors calculate costs of almost €13 billion for the period 2018 to 2020. Overall, reviewing the literature indicates that loss and damage in agriculture and forestry due to heat and drought stress is, while being driven by some extreme years, substantial. At the same time, these estimates are underrepresented in databases which serve as a reference point for the overall loss and damage of weather- and climate-related events in Germany. A key reason for the underrepresentation is a lack of insurance information and data limitations that constrain modelling approaches. Taken together, this stresses the need for a comprehensive, but pragmatic approach that utilizes publicly available information to gauge loss and damages from heat and drought periods in Germany. This paper describes a method to close the gap in loss and damage data of heat- and drought-related events at the example of the heatwaves and droughts in 2018/2019 in Germany. However, before the method is depicted in detail, a closer look is taken at the exceptionally hot and dry two years 2018 and 2019.

3 The impact of heatwaves and droughts in Germany in 2018 and 2019

From a meteorological perspective, the years 2018 and 2019 in Germany were extreme. Against the background of a long-term observation, Germany experienced exceptionally hot days with temperatures over 30 °C – which correspond to the definition of so-called “heat day” (Pissarskoi, v. Möllendorff & Sterba, 2015). Days like these are hardly tolerated by unadapted humans - the heart rate increases, work is perceived as considerably more stressful and a decrease in concentration leads to increased susceptibility to errors and accidents. In addition, high temperatures increase susceptibility to illness and mortality, especially among older and weakened people (Hübler, Klepper, & Peterson, 2007). Besides the consequences for human health and working productivity, the rising temperatures also implied consequences for industries through drought events. The high temperatures resulted in high soil moisture evaporation rates, leading in combination with below-average precipitation to negative climate water balances (García-Herrera et al., 2019). In the following, a closer look is taken at both heat and drought events in the two years 2018 and 2019. Particularly in the case of droughts it becomes clear how the events of both years are interconnected. Thus, the two years are proposed to be evaluated together in the following.

The periods of heat days that Germany experienced in 2018 were significantly above-average nationwide. The first days with temperatures above 30 °C were recorded as early as April (e.g., 30.4 °C in Ohlsbach on April 22). Between May and June, temperatures of up to 34 °C occurred throughout Germany (Imbery et al., 2018). The 35 °C mark was exceeded in Germany for the first time on July 24th (35.9 °C in Lingen) (Mühr et al., 2018). In the following period up to August 9th, temperatures exceeded 30 °C daily throughout Baden-Württemberg, Bavaria, Rhineland-Palatinate, and Hesse. A particularly long heat wave occurred in Lower Franconia, the Rhine-Main area, and parts of Baden-Württemberg, with 18 heat days in a row (Imbery et al., 2018). Overall, Germany recorded in 2018 more than 20 heat days on average, considering the whole nationwide area, representing almost twice as many as the average for the 2010 to 2020 decade (with an average of 11 days) (Kaspar, Friedrich & Imbery, 2020). All in all, 2018 was the warmest year in Germany since weather records began in 1881.

The summer of 2019 was also exceptionally hot nationwide. Although the spring was somewhat cooler than in the previous year, June 2019 was declared to be the warmest June since the beginning of weather recordings (Meinert et al., 2019). Nationwide, 437 weather stations recorded a hot day of over 30°C in June, and 223 weather stations recorded at least 35°C (Imbery et al., 2019). In July, it got even hotter. During an extreme heat wave from July 24th to 26th, temperatures of over 40°C were recorded every day in Germany (Deutscher Wetterdienst, 2019; Imbery et al., 2019). A heat wave of such magnitude occurred in Germany for the first time since records began (Bissolli et al., 2019). Overall, there were nearly 17 heat days in Germany in 2019 on average, considering the whole nationwide area. The year 2019 was considered the second warmest year both in Germany and globally (Kaspar, Friedrich & Imbery, 2020), but was pushed from second to third place by 2020.

The combination of rising temperatures and below-average precipitation fostered drought events in the years 2018 and 2019. The dry period began in 2018 in Central Europe as early as February, and the precipitation deficit persisted in the following months. On average, only about 60% of the usual rainfall occurred in Germany between February and August 2018 (Mühr et al., 2018; Imbery et al., 2018). Only the year 1911 was even drier in the period April to August (Imbery et al., 2018). For the entire year 2018, studies by the German Meteorological Office (DWD) indicate a precipitation amount of less than 75% compared to the 1961 to 1990 reference period (Meinert et al., 2019). The year 2018 was thus one of the years with the lowest precipitation since 1881 (Imbery et al., 2018). The drought resulted in increasing drought stress in the second half of the year. The drought in 2018 was a particularly large-scale event in this regard. Starting in August, almost all of Germany was unusually dry and affected by drought in November. For comparison: In the heat summer of 2003, a maximum of 74% of the nationwide area was affected by drought. The last similar large-scale event occurred in 1976 (Mühr et al., 2018). Nationwide, soils were drier in the summer and fall of 2018 than in any previous year in the drought monitor available since 1951.

The consequences of the 2018 summer drought continued to have an impact into 2019. Thus, croplands across Germany started with severe to exceptional drought stress in the overall soil. Although above-average precipitation in January and March 2019 brought relief, especially in the topsoil, the prevailing precipitation deficit was only slightly reduced (Meinert et al., 2019). In April, only 60% of the usual precipitation amount fell. In summer, thunderstorms led to high precipitation amounts on isolated days in some areas. Overall, however, the annual precipitation target was clearly missed by 27% (Deutscher Wetterdienst, 2019). The high temperatures in June increasingly strained the soil moisture in most of Germany at the beginning of July. In some cases, soil moisture levels even fell below the low values recorded in the previous year 2018. North Rhine-Westphalia, Lower Saxony, Mecklenburg-Western Pomerania, Brandenburg, Saxony-Anhalt, Saxony, and Thuringia were particularly hard hit, recording the lowest soil moisture levels since measurements began in 1961 (Meinert et al., 2019; Deutscher Wetterdienst, 2019).

In sum, 2018 and 2019 were characterized by high temperatures and low precipitation rates. The high temperatures affected human health and working productivity. However, the combination of high temperatures and low precipitation rates also brought economic consequences for water-intensive industries such as agriculture or forestry.

Impacts on the agricultural, forestry and industrial sector

The combination of the high temperatures and the lack of rainfall led to two consecutive summers of drought in 2018 and 2019 in Germany, with a significant impact on the agricultural production (Bundesministerium für Ernährung und Landwirtschaft, 2019). Direct losses in agriculture resulted from the heat- or drought-related decline in crop quantity and quality: crop growth was affected by heat stress and lack of water, and in addition, an increased incidence of pests was recorded, favored by the already weakened plants. The crop losses recorded varied from region to region: while the national average of crop losses was around 20%, losses of up to 70% were recorded for individual crops in northern and eastern Germany. For the fruit harvest, on the other hand, the warm summer of 2018 in particular was actually beneficial - here, the production value increased by over 50% (Bundesministerium für Ernährung und Landwirtschaft, 2019). The indirect damage caused by climate change impacts on agricultural production occurs both in agriculture itself and in downstream industries, as well as among consumers. In the case of livestock, for example, the aforementioned effect of growth and quality losses can also be triggered by a climate change-induced shortage of feed. In order to counteract this feed shortage, crops for which an alternative use (with higher prices) was planned are partly fed or, in extreme cases, animal slaughter is preferred. In both cases, losses and additional costs result from deviations from the expected or possible revenue value.

Germany's forests also suffered greatly from the heat and drought extremes of 2018/2019. Abiotic (storms, forest fires, heat, drought) and biotic (insects, fungi) factors caused massive damage to forest inventories. The causes of forest damages are not only diverse, but also interdependent. For example, pests such as the bark beetle can multiply particularly quickly in trees already weakened by drought (Umweltbundesamt, 2018). Damaged trees also exhibit lower storm resistance. The heat and drought extremes in 2018/2019 led to a significant increase in the volume of damaged wood as well as logging. With 49% and 67%, respectively, the share of damaged wood felling of total felling in 2018 and 2019 was more than two to three times higher than in 2010 with a share of around 20% (Statistisches Bundesamt (Destatis), 2020).

Besides the agricultural and forestry sector, the industrial sector was also affected by the hot temperatures through a decline in working productivity. Exposure to heat reduces the ability to concentrate and leads to more frequent or severe occupational accidents (Kjellstrom et al., 2016). Thus, overall work productivity decreases on hot days, especially in physically demanding or outdoor occupations such as physical work in outdoor industries such as agriculture, forestry, mining or construction. However, also service as well as transportation-related activities suffer from declined working productivity on hot days.

As all three mentioned sectors provide robust statistical data that can be used to quantify losses and damages through an indicator-based approach, the following chapter describes in detail, how these losses and damages from heat- and drought-related events can be quantified at the example of the heatwaves and droughts in 2018/2019 in Germany.

4 Quantifying the economic losses of Germanys heatwaves and droughts in 2018/2019

As indicated by Figure 2 existing databases only track a fraction of possible loss and damage information, specifically the data which can be recorded and monetarized by the means of valid indicators. Robust data on indirect costs as well as non- or hardly monetizable aspects of climate change are still missing. While in the context of this study not all impacts of heat and droughts could be considered, we present a feasible procedure on how to include indirect effects into the loss and damage calculations.

The quantification of climate-related damage from the heat and drought extremes of 2018/2019 in this study is carried out with the help of so-called damage indicators. A damage indicator combines the respective affected sector (agriculture, forestry, or industry/trade) of the German Adaptation Strategy (DAS) with the concrete climate impact (heat- or drought-related) that led to the damage. Examples of a damage indicator are "crop losses in agriculture due to heat-related crop failures" or "losses in industry and trade due to heat-related productivity reduction". In principle, a damage indicator can be created for any combination of sector and climate impact. However, this is not expedient due to the resulting complexity of the impact relationships and the partial lack of economic relevance of the resulting indicators. Generally, it is rather important to identify the most

relevant or impactful damage indicators in order to obtain a sound estimate of the overall extent of damage from the 2018/2019 heat and drought extremes. An example of a proxy indicator of "agricultural damage costs due to heat" is represented by "crop losses in agriculture due to heat-related crop failures". The latter is better supported by data and thus illustrates a more relevant and impactful damage indicator than the former. While it is impossible to capture agricultural damage in a holistic manner, an estimate of wheat crop losses provides a sound starting point supported by data.
The Climate Risk and Vulnerability Analysis (KWRA) of 2021 with a total of 102 climate impacts, provides a starting point for identifying potentially relevant damage indicators (Kahlenborn et al., 2021). Only a subset of the indicators is essential for capturing the extent of damage from the 2018/2019 heat and drought extremes. A first narrowing down can be done by selecting the DAS sectors where high absolute (in the context of the German economy) or high relative (in the context of the relevance of the damage level for the respective field of action) damages are assumed and can be operationalized. Based on Hirschfeld et al. (2021) and the KWRA 2021 (Kahlenborn et al., 2021), the DAS sectors industry and commerce, agriculture, forestry, and construction are selected. A second constraint of the 102 KWRA impacts is the relevance of the damage indicators for the specifically considered damage event “heat and drought extremes in the summers of 2018 and 2019”. By selecting the indicators related to the event, a total of six indicators remained. The damage effects of those indicators will be quantified in the following and are thus used for an estimation of the magnitude of the loss and damage from the heat and drought extremes in 2018 and 2019:

- Yield losses of winter wheat due to heat and drought,
- Yield losses of silage maize due to heat and drought,
- Yield losses of other crops due to heat and drought,
- Impairment of the quality & availability of wood due to heat and drought,
- Impairment of forest ecosystem services – costs due to losses in climate change mitigation services,
- Heat-related reduction in labor productivity.

These six damage indicators refer to the direct loss and damage caused by heat or drought-related events. In addition to the direct costs of climate change we also include an estimation on the indirect effects of these costs along value chains based on ratios of indirect to direct costs, identified by Sieg et al. (2019) for 19 economic sectors for Germany in the case of climate-related disasters. In the following, the approach to estimate the direct and indirect costs induced by the heatwaves and droughts in 2018/2019 will be described in detail for each of the three selected sectors (agriculture, forestry, industry/trade).

4.1 Agriculture

Economic losses in agriculture are composed of the following three damage indicators:

- Yield losses of winter wheat due to heat and drought,
- Yield losses of silage corn due to heat and drought,
- Yield losses of other crops due to heat and drought.

The formula for determining the losses is the same for all three indicators:

$$
\begin{aligned}
loss\ in\ year\ t = (\ & crop\ area\ in\ year\ t \\
& x\ average\ yield\ per\ hectare\ in\ the\ period\ t-5\ to\ t \\
& x\ average\ selling\ price\ in\ the\ period\ t-5\ to\ t\ ) \\
& -revenue\ in\ year\ t
\end{aligned}
$$

The calculations are based on the data from the official harvest statistics of the German Federal Ministry for Food and Agriculture (BMEL), as well as annual price statistics from Eurostat (see Annex, Table 6). The yield calculation of silage corn is more difficult, in contrast to the other field crops, because the majority of silage corn is not sold, but is used on-farm (e.g., as animal feed), so that there are few reliable official price statistics. The calculation here is based on data from the Austrian Chamber of Agriculture and shows that silage corn prices at an average yield level are about 17.5% of the grain corn price. If a ton of grain corn sells for €165 in a year, the price of silage corn is assumed to be about €29 per ton (Landwirtschaftskammer Österreich, 2021). The official harvest statistics of the BMEL for the two years 2018 and 2019 may reflect besides heatwaves or droughts also other events such as heavy rain, storms or hail events. However, since these events tend to have a small-scale effect, the impact is estimated to be rather low. It is therefore assumed that changes in harvest volumes and yields are attributable to the drought events. The Natural Hazards Report of the German Insurance Association (GDV) also supports this assumption: In both 2018 and 2019, comparatively low costs were incurred in property insurance due to windstorm and hail (€2.2 billion and €1.8 billion, respectively), but these are distributed among the areas of residential buildings, households, industry, and commerce as well as agriculture, so that the agricultural share of losses here is still to be estimated as significantly lower (Gesamtverband der Deutschen Versicherungswirtschaft e.V., 2020). Since more than two-thirds of agricultural land is insured against hail (Bundesministerium für Ernährung und Landwirtschaft, 2017), hidden damage that does not appear in the insurance statistics cannot be assumed.

Analyses of the ratio of direct to indirect losses in agriculture in different regional contexts of drought and heat events indicate that indirect consequential losses in agriculture during drought account for a high proportion of total losses. Depending on the study and its context, the ratio of direct to indirect damages ranges from 0.6 (Wittwer, Madden & Horridge, 2003) to 0.85 (Martin-Ortega Julia, Gonzalez-Eguino & Markandya, 2012; Diersen, Taylor & May, 2002). Consequently, one euro of direct damages entails between 60 and 85 cents of indirect damages. As Sieg et al. (2019) do not provide a ratio of direct to indirect costs for the agriculture sector we use the identified ratios from the literature as a baseline for assessing the total indirect costs.

4.2 Forestry

Economic losses in forestry are composed of the following two damage indicators:

- Impairment of the quality & availability of wood due to heat and drought,
- Impairment of forest ecosystem services – costs due to losses in climate change mitigation services.

In this study, the recording of damage from the 2018/2019 heat and drought extremes in forestry is carried out across all felling causes and formally attributes them to the weather extremes of heat and drought, as these are the decisive factors for an emerging felling due to general weakness or instability of a tree, pest infestation or storms. This serves to provide consistency in the logic of the damage indicators as an interaction of DAS sector, cost dimension, and extreme event.

Losses due to calamity

High levels of damaged timber felling lead to societal costs in several respects. The trees infested by the bark beetle must be felled and transported out of the forests as quickly as possible, resulting in additional costs and reduced revenues in the operations. Moreover, the reforestation of felling areas must be financed. In addition, the damaged wood can only be sold at a discount due to oversupply. In some cases, calamity discounts of 10% to 45% per tree species must be

expected (Möhring et al., 2021). In total, a high proportion of damaged timber can lead to considerable reductions in the sale of the logs.
The calculation of the calamity-related additional operational costs in the raw timber production because of the heat and drought extremes 2018/2019 is mainly based on the data and assumptions of Möhring et al. (2021). Based on a damaged wood volume of about 104 million harvested solid cubic meters, a damaged wood harvest of about 76 million cubic meters in 2018/2019 is determined minus the forest areas with use restrictions as well as unutilized and unprocessed damaged wood (see Annex, Table 7).
Assuming calamity-related revenue reductions as well as average timber revenues, the calamity-related reduced revenues of the damaged timber can be calculated. Spruce not only represents the majority of the damaged timber, but it also has the highest prices per cubic meter and is most affected by calamity-related revenue reductions. As a result, a large part of more than 90% of the operational damage costs is due to reduced revenues in the sale of spruce, while pine (5.3%), beech (3.4%) and oak (0.5%) play a subordinate role.

Operational costs due to calamity

In addition to reduced revenues, the forestry sector faces additional costs. Assuming a flat-rate calamity-related cost surcharge of 15% (about €300 million, see Annex, Table 8), an amount of damaged timber to be written off (about €680 million, see Annex, Table 10), additional costs in reforesting the calamity area (about €800 million, see Annex, Table 11), and other additional operational costs (about €350 million), the calamity-related additional operational costs in raw timber production can be estimated.

Losses in additional value-added

The damage caused by the heat and drought extremes of 2018/2019 to the forest inventory is not limited to an increased volume of damaged wood; it is also reflected in growth losses of the remaining forest inventory. These growth losses can be substantial. For example, Beck (2010) estimates the growth losses of the 2003 dry spell over a 4-year period for spruce to be 119% of the average annual growth of a tree. Again, we follow the calculation approach of Möhring et al. (2021) and base the estimated growth losses on the relative growth losses estimated in Beck (2010) over a 4-year period as a result of the 2003 drought year. Specifically, we make a highly simplifying assumption that growth losses due to the 2018/2019 heat and drought extremes are 1.3 times the 2003 drought year.

Costs due to immaturity

Furthermore, a high volume of damaged timber also leads to further costs for the company and society, which are difficult to quantify in monetary terms. For example, losses due to immaturity at the time of cutting must be added to the calamity deductions. The term "immaturity" here refers to the loss of future yields due to the loss of yield potential that is normally still inherent in the forest inventory. By losing the yield potential that is normally still inherent in the inventory, forestry companies indirectly lose further revenue due to immaturity. Considering some correction factors in the so-called age value factor method by Möhring et al. (2021), the losses due to immaturity are estimated. In addition, not all damaged timber is processed and sold. It is critical to the long-term viability of forest operations that reforestation be practiced on calamity areas. This can also lead to additional costs compared to normal cultural costs (Möhring et al., 2021).

Losses in ecosystem services

Besides, a reduction in forest cover also leads to a loss of ecosystem services – the second damage indicator for the forestry sector. For example, the forest inventory contributes to climate

mitigation in its function as a sink for CO_2. Depending on the use of the wood, the carbon harvested in the forest is transferred into wood products, where it is released again after the wood products have reached the end of their life. A calamity-induced loss of the forest inventory thus also leads to a loss of CO_2 storage capacity and thus climate mitigation services (Möhring et al., 2021). To calculate the societal costs of the reduced climate change mitigation services, this study follows the approaches of the Thünen Institute's regionalized assessment of forest services in Germany (Elsasser, Altenbrunn, Köthke, Lorenz & Meyerhoff, 2021). The assumed use distribution and resulting substitution of tree species in this study follows Elsasser et al. (2021) and is shown in Table 13 in the Annex. The calculation of the reduced CO_2 storage capacity is done in two steps. In a first step, the amount of CO_2 bound in the damaged wood is determined. For this purpose, differentiated for each tree species, the wood mass is first calculated based on the kiln density. Since about half of the wood mass consists of carbon, the kiln density is divided by a factor of two to obtain the weight of carbon stored in the tree. The conversion to CO_2 equivalents, and thus the CO_2 storage capacity of the damaged wood, is done by the fixed conversion factor of 3.67.
In a second step, the amount of released CO_2 is determined. Two important assumptions underlie the calculation of the amount of CO_2 released by the reduced CO_2 storage capacity. The first assumption concerns the assumed shares of utilization methods of the reclaimed damaged wood. Depending on the use of the wood, the carbon harvested in the forest is released again (e.g., through energy recovery) or remains stored for a long time in wood products (e.g., in durable constructions such as buildings or furniture). In the distribution of use cases, a distinction is essentially made between the use of hardwood and softwood. The second assumption is that of substitution effects. Both the energetic and the long-term material usage of wood lead to a reduced use of other materials such as steel or concrete (material substitution) as well as fuels (energetic substitution). Thus, the net amount of CO_2 released associated with the increased occurrence of damaged wood is crucial for capturing the societal costs of reduced climate mitigation services. According to Elsasser et al. (2021), material use of wood results in net carbon savings from reduced use of non-wood products. Energy substitution, on the other hand, is assumed to result in a net increase in CO_2. The change determined in this way is then multiplied by a cost rate based on the range of emission prices currently in circulation in Germany and publications on the social costs of CO_2 (Matthey & Bünger, 2020). A substitution value of less than 1 means that there has been a net increase in CO_2 released because of the emergence of masses of damaged timber, and thus societal costs in terms of reduced climate change mitigation services are occurring. Combining this with the information from the processed deforestation results in an estimated net amount of CO_2 released of approximately 14 million metric tons. Assuming different cost approaches for one ton of CO_2, which can range from €50 (lowest price in the EU Emissions Trading Scheme since July 2021) to €201 (UBA reference price of social CO_2 costs), the societal costs due to losses in climate protection services are calculated.

Indirect costs

In addition to the forestry operations directly affected, companies along the value chain are also indirectly affected by damage in raw wood production. Analogous to the ratio of direct to indirect damages in agriculture, a factor between 0.6 and 0.85 is applied to calculate indirect damages (Ní Dhubháin, Fléchard, Moloney & O'Connor, 2009; Wittwer et al., 2003; Martin-Ortega et al., 2012; Diersen et al., 2002).

4.3 Productivity reduction in industry and trade

Economic losses in industry and trade are composed of the following damage indicator:

- Heat-related reduction in labor productivity

A large body of research agrees that working productivity declines with increasing temperatures but differs in the magnitude of the specific effects identified. A consistent framework of productivity reduction for Germany is presented by Hübler et al. (2007), who use a threshold temperature of 26 °C and a productivity loss between 3 and 12% (based on research by Bux (2006)) in their approach. According to Seppänen et al. (2004), each additional degree above a threshold of 25 °C decreases productivity by about 2%. Following this assumption, on days with a temperature of 30 °C, the productivity is consequently only 90% of the working productivity with temperatures below 25 °C, unless the corresponding workplace has adaptation or cooling measures, which is consistent with the approach of Hübler et al. (2007). Due to the lack of detailed climatic and socioeconomic data for Germany as a whole, only the reduction in labor productivity on days above 30 °C can be calculated for the indicator in this study. However, since a large number of days occurred, especially in 2018 and 2019, on which the temperature was significantly above the 30 °C threshold (the exact number of which could not be determined for each federal state), the upper limit value of a productivity reduction of 12% for each day with T_{max} > 30 °C is taken from Bux (2006) and Hübler et al. (2007) for the following calculation.
For each German federal state and a total of 19 different economic sectors (due to the different climatic conditions as well as economic output and gross wages), the productivity reduction effects were calculated separately using the following formula:

$$\begin{aligned} productivity\ reduction = \ & number\ of\ days\ with\ Tmax > 30\ °C \\ & x\ number\ of\ hours\ with\ Tmax > 30\ °C\ on\ heat\ days \\ & x\ number\ of\ full-time\ equivalent\ employees \\ & x\ average\ gross\ hourly\ wage \\ & x\ non-adaption\ factor \end{aligned}$$

The statistical data on full-time equivalent employees as well as the gross hourly wages is taken from the German Statistical Office (DESTATIS), whereas data on the number of heat days per federal state was taken from the German Meteorological Office.
The assumption is made that on a heat day with 30 °C, the temperature is above 30 °C for four working hours (around midday/afternoon). The other four working hours are not included in the productivity reduction calculation (as they are assumed to be below 30 °C). Multiplying the number of heat days per federal state by the four assumed working hours yields the respective number of working hours per federal state to which the reduced productivity factor of 88% is to be applied. In order to determine the economic value of the productivity loss during the heat hours, the total volume of conducted work in the years under investigation (disaggregated by 19 economic sectors and the 16 federal states) is converted into full-time equivalents. The number of full-time equivalents is then multiplied by the gross hourly wage for the industry and federal state in question and the number of heat hours.
The resulting total productivity during the heat hours is then multiplied by the reduced productivity factor of 88%, as well as a so called "non-adaptation" factor. The non-adaptation factor thereby expresses how many full-time equivalents cannot benefit from adaptation measures that keep the ambient temperature below 30 °C. Only in these does the productivity loss actually occur. In particular, the non-adaptation factor is higher in physical and outdoor occupations, such as construction or agriculture, than in service industries. However, the source material on air conditioning coverage, which is seen as the (in economic terms) most effective adaptation measure, is poor or based on studies conducted a long time ago. In particular, a sector-specific estimation of coverage is not

possible on the basis of these: as an alternative approach, four groups of economic sectors were formed based on existing studies:

- Outdoor industries characterized by physical work (agriculture, forestry, mining, construction): Here, coverage with adaptation measures is assumed to be 0%.
- Manufacturing, retail, and other non-office service activities: Here, based on the coverage of air-conditioned non-residential buildings according to Bettgenhäuser et al. (2011) with air-conditioning systems, a coverage with adaptation measures of 33% is assumed.
- Services taking place in office buildings (financial and insurance services, real estate and housing, professional, scientific and technical services, information and communication, etc.): Here, also based on Bettgenhäuser et al. (2011), the assumption is made that 51% of office space is air-conditioned.
- Transportation-related activities (traffic and logistics): This group, characterized by occupations that do not take place indoors (e.g., transport and logistics services in trucks, as well as public transport services), are largely carried out in air-conditioned cabins, so that a coverage with adaptation measures of 60% can be assumed.

Based on the development of the number of total air-conditioning systems according to figures from the International Energy Agency (International Energy Agency, 2018), a growth rate of 2% per year is assumed for Germany in order to be able to determine the coverage with air-conditioning systems also for the years 2018 and 2019. In this context, the reduction in productivity in the respective sectors also entails indirect effects: missing, delayed or intermediate inputs with less quality can also result in further production losses in downstream sectors along the value chains. In the following, the indirect effects of productivity losses due to heat are determined based on a modeling approach originally developed by Sieg et al. (2019) for calculating indirect effects due to flood damage. Sieg et al. (2019) use an industry-specific supply-side input-output model for this purpose. Following the logic that the mode of origin (heat or flood) of a production loss is irrelevant in the context of input-output modeling and results in the same consequential effects, the approach can also be applied to the calculation of indirect effects due to heat, especially since in this case only the ratio of direct to indirect effects according to Sieg et al. (2019) is used, not the absolute damage amounts. Using this approach also has the advantage that all factors come from the same consistent model and can be mapped in an industry-specific manner. The ranges described in Table 5 of the Annex represent the 90% confidence interval (except for agriculture, forestry, and fisheries, for which the sources and their ranges identified in chapter 4 apply).

5 The economic losses of Germanys drought and heatwaves in 2018/2019

5.1 Economic losses in agriculture

Direct losses for winter wheat in 2018 and 2019 were just under €1 billion. For silage corn, direct losses were around €830 million. By far the largest share of direct losses can be attributed (at around €2.6 billion) to all other crops, resulting in total direct losses of around €4.4 billion. The year 2018 is responsible for around two-thirds of the losses in both years. Summing up the damages across all three examined indicators of the sector agriculture, the total direct damages for 2018 amount to €2.99 billion, plus €1.79-2.54 billion of indirect or downstream damages. For 2019, the direct damage amounts to €1.44 billion, to which a further €0.86-1.22 billion in indirect damage is added. Overall, the climate change-related heat and drought extremes in 2018 and 2019 thus result in total losses of between €7 billion and €8.2 billion (see Table 1).

Table 1: Composition of total damages for loss in revenue in agriculture

	Expected revenue	Actual revenue	Loss	Range of indirect effects (factor 0.6)	(factor 0.85)	total damage
Winter wheat						
2018	4,090	3,410	680	408	578	1,088-1,258
2019	4,163	3,851	312	187	265	500-578
Total	**8,253**	**7,261**	**992**	**595**	**843**	**1,588-1,836**
Silage corn						
2018	2,767	2,238	529	318	450	847-980
2019	2,805	2,506	298	179	253	477-552
Total	**5,572**	**4,744**	**828**	**497**	**704**	**1,324-1,531**
Other crops						
2018	9,248	7,470	1,778	1,067	1,511	2,844-3,288
2019	9,912	9,086	826	495	702	1,321-1,527
Total	**19,160**	**16,557**	**2,603**	**1,562**	**2,213**	**4,165-4,816**
Sum of all crops						
2018	16,105	13,118	2,987	1,793	2,539	4,779-5,526
2019	16,880	15,443	1,436	861	1,220	2,298-2,657
Total	**32,985**	**28,562**	**4,423**	**2,654**	**3,760**	**7,077-8,183**

Own calculation and representation. **Data Source: Statistisches Bundesamt: Fachserie 3, R 3.2.1, Feldfrüchte 2020 und Eurostat:** Selling prices of agricultural products (absolute prices) 2021
All figures in € million

5.2 Economic losses in forestry

Overall, the damage caused by the 2018/2019 summer extremes in raw timber production adds up as follows: Across all tree species, calamity-related reduced revenues add up to almost €2 billion (see Annex, Table 8). The estimated losses due to immaturity amount to about €1.3 billion or about €5,700 per hectare (see Annex, Table 9). The estimated calamity-related additional operational costs in raw timber production total more than €2.1 billion. Lastly, the losses in additional value added amount to over €3.0 billion (see Annex, Table 12).
For forestry operations in Germany, this means that approx. €8.47 billion losses were incurred. In this case, indirect damages amount to an additional €5.1 billion to €7.2 billion (see Table 2). Additional societal costs due to losses in ecosystem services range from €0.7 to €2.8 billion.

Table 2: Composition of total damages in forestry (excl. climate protection services)

	Direct costs	Range of indirect effects: factor 0.6	Range of indirect effects: factor 0.85	total damages
2018	€ 2.89 billion	€ 1.74 billion	€ 2.46 billion	€ 4.63 – 5.35 billion
2019	€ 5.58 billion	€ 3.35 billion	€ 4.74 billion	€ 8.93 – 10.32 billion
Total	**€ 8.47 billion**	**€ 5.09 billion**	**€ 7.20 billion**	**€ 13.56 – 15.67 billion**

Own calculation based on Möhring et al. (2021)

5.3 Economic losses in the industry sector

For 2018, direct losses due to heat-related productivity losses are calculated at €2.73 billion; for 2019, direct losses are only slightly lower at €2.27 billion. This results in total direct damages of around €5 billion (see Annex, Table 14). The largest share of total direct losses (in both 2018 and 2019) occurred in the manufacturing sector - totaling over €1.2 billion. This is due to the large number of people working in this sector combined with the low coverage of corresponding adaptation measures. The situation is similar in the health and social services sector, which accounted for almost one-sixth of the total losses (€840 million). With €540 million in direct losses over the two years, the construction industry is also heavily affected by heat-related productivity losses.
In addition to the large direct effects, the manufacturing sector also exhibits high ranges of indirect effects. For example, €1 of direct losses due to heat-related productivity losses leads to indirect costs of €1.53 to €2.39 here. In absolute terms, this means indirect losses of between €1.02 and €1.59 billion in 2018 and between €0.85 and €1.32 billion in 2019. By contrast, in health care and social assistance, which was responsible for the second-highest direct effects, the range is only €100 million to €160 million (for 2018) and €85 million to €135 million (for 2019). Adding up all the ranges of indirect effects shows that they totaled between €1.9 billion and €2.89 billion for 2018; for 2019, the effect is between €1.58 billion and €2.4 billion, (see Annex, Table 15), so that the indirect effects of heat-related productivity losses alone resulted in economic losses of between €3.5 billion and €5.3 billion over both years. If the total direct losses are added to this, a 90% confidence interval of the economic effects of heat-related productivity losses of €8.5 to €10.3 billion emerges (see Table 3), with a median value of around €9.2 billion.

Table 3: Composition of total damages due to heat-related productivity losses

	direct damages	Range of indirect effects		total damages	
2018	2,727	1,902	2,893	4,629	5,620
2019	2,267	1,579	2,400	3,846	4,668
Total	**4,994**	**3,481**	**5,293**	**8,475**	**10,288**

Own calculation. All figures in € million

5.4 Comparing loss and damage of heat and drought with the flash floods of July 2021

In mid-July 2021, several locations in western and central Europe experienced persistent and recurring heavy precipitation over a period of several days. Parts of the German states of North Rhine-Westphalia and Rhineland-Palatinate were particularly affected. In western Germany, precipitation levels reached their daily maximum on July 14th 2021, with rainfall amounts of up to 150 liters per square meter within 24 hours. In addition, the 2021 heavy rain event was characterized by an exceptionally large spatial extent, extending from Belgium to northern Hesse with partial impacts and damage even in Bavaria and Saxony (Kreienkamp et al., 2021).
The German Insurance Association puts the amount of insured at €8.2 billion (Gesamtverband der Deutschen Versicherungswirtschaft e.V., 2022). In its official application for aid from the EU Solidarity Fund, the German government indicated losses of €29.2 billion. A report published in March 2022 by the German Federal Ministry of the Interior and Federal Ministry of Finance indicates damages of €33.1 billion (excluding deployment costs of approximately €300 million) and distributes these damages among various categories (e.g., "damages to companies" or "damages to municipal infrastructures," Bundesministerium des Innern und für Heimat & Bundesministerium der Finanzen, 2022). Based on this information, Trenczek et al. (2022) calculated a total damage (including indirect effects) of €40.5 billion. Although it cannot be conclusively determined what proportion of the damage that occurred can be attributed to anthropogenic climate change, studies for both the flash floods and the 2018/2019 heat and drought period show that there was a correlation between their occurrence and the continuous emission of greenhouse gases (Kreienkamp et al., 2021 and Vautard et al., 2019).
A comparison of the two events studied also shows that the total extent of damage differs by only about €5 billion, and thus has relatively similar magnitudes. Major differences exist in the composition of the damage: Whereas drought and heat damage mainly affect agriculture and forestry, flash floods and flood events mainly affect the construction sector as well as transport and logistic infrastructure. The industry and commerce sector is strongly affected by both types of events. People are also affected differently between the two events: Despite the high number of fatalities during the 2021 flash flood (183 fatalities) for a flash flood event, these are still significantly below the observable fatalities due to heat (according to Trenczek et al. (2022) about 7,500 in 2018 and 2019 in Germany). In terms of monetary damages, the 2021 flash flood resulted in a high impact due to damages to private households or buildings, while the costs of heat events primarily affect business activities. Another difference between the two types of events is the ratio of direct to indirect total damage. While the ratio of direct to indirect losses is high at 1:0.7 for summer extremes (due to the high impact on the primarily producing or processing sectors of the economy), it is only 1:0.2 for the flash floods of July 2021.
In combination with the high death toll of a heat event, this confirms the picture of a rather slow-acting or little visible and discussed extreme event in contrast to the short but intense, visually impacting and thus strongly persisting in the collective memory heavy rain or flash flood events. This shows that in Germany, especially in the field of heat and drought prevention, there are still large adaptation and knowledge gaps regarding the actual damage caused by heat and drought events.

6 Conclusion and further research

Heat and drought extremes have led to enormous damage in Germany. Combining all previously mentioned and calculated damage indicators we find a total damage of approximately € 35 billion (see Table 4).

Table 4: Composition of all considered costs due to climate change impacts of heat and drought extremes in 2018 and 2019 in Germany

		2018			2019			2018 and 2019 combined		
sector	**name of indicator**	**direct**	**indirect**	**total**	**direct**	**indirect**	**total**	**direct**	**indirect**	**total**
Agriculture	Yield loss of winter wheat due to heat and drought	680	408 – 578	1,088 – 1,258	312	187 – 265	500 – 578	992	595 – 843	1,588 – 1,836
	Yield loss of silage corn due to heat and drought	529	318 – 450	847 – 980	298	179 – 253	477 – 552	828	497 – 704	1,324 – 1,531
	Yield loss of other crops due to heat and drought	1,778	1,067 – 1,511	2,844 – 3,288	826	495 – 702	1,321 – 1,527	2,603	1,562 – 2,213	4,165 – 4,816
Forestry	Costs in production of raw wood	2,891	1,735 – 2,457	4,626 – 5,349	5,579	3,348 – 4,742	8,927 – 10,322	8,471	5,082 – 7,200	13,553 – 15,670
	Costs due to losses in climate protection services	974		974	1,879		1,879	2,853		2,853
Trade and industry	Heat-related decline in labor productivity	2,727	1,902 – 2,893	4,629 – 5,620	2,267	1,578 – 2,400	3,845 – 4,667	4,994	3,480 – 5,293	8,474 – 10,287
Total		**9,579**	**5,430 – 7,889**	**15,008 – 17,469**	**11,161**	**5,787 – 8,362**	**16,949 – 19,525**	**20,741**	**11,216 – 16,253**	**31,957 – 36,993**

Own calculation and representation. Any variation in the summations is due to rounding uncertainties. Indirect damages indicate the 90% confidence interval of the occurring ranges.

So far, no comprehensive picture on the monetized costs linked to these extremes was available. The present study takes a first step in closing this gap on the basis of selected, robust damage indicators. It is important to note that as this study only incorporates impact chains based on specific indicators, the presented numbers are to be interpreted as the lower margin of the actual loss and damage. Some of the most impactful effects of heat and drought (e.g., on biodiversity and human health) could not be included in this study. Here, further research in monetizing and incorporating these damages into the calculations is needed. Additionally, we only researched loss and damage numbers on a limited spatial and temporal scale. Further systematic analyses are needed for more countries as well as additional years.

However, there is also a need for further research on the distribution of the total costs incurred in relation to heat events. Previous approaches do not sufficiently discuss the distribution of damages in terms of gender or other social aspects. The approach presented here can also only do this through a qualitative interpretation of the data: Looking into the sectors agriculture as well as mining and construction, they are characterized by precarious working conditions. The combination of a high exposure to heat, high physical strain and lower-than-average income structures suggests that workers in these sectors are more vulnerable to the effects of high heat (and often also have only low adaptive capacities in their home or private environment). A breakdown of heat-related productivity losses by age group would also provide further insight into the social component of occurring damages but was not pursued in this study due to a lack of research data on age-specific heat-related productivity losses.

More research is also needed particularly in the area of attributing incurred losses to climate change. The costs of approximately €35 billion calculated in the present study include damages attributable to high temperatures or drought phenomena. However, they do not provide any information on the share of damage actually attributable to climate change or on the share of damage that could have been expected in a year with a “normal” climate. This is due to the core statement of attribution research: The attribution only reflects the change in the statistical probability of occurrence of a specific event due to climate change but does not determine how much a specific event has intensified due to climate change. One way of approaching the attributable damage here would be through the annual damage expectation value of an event. For the events of the year 2018, there is no reliable attribution statement for Germany, only for Northern Europe. The research suggests an up to five times increased recurrence frequency of the event was found (World Weather Attribution, 2018). The events of 2019, which caused €18.5 billion of the total €35 billion in damages according to the present study, are classified for Germany as events with "return periods between several decades and a few centuries". More specifically, according to the attribution research, the probability of occurrence was increased by a factor of 10 due to climate change (Vautard et al., 2019).

A back of the envelope calculation illustrates the differences in the annual damage expectation value. Assuming the event recurs every 100 years, which according to WWA is the upper limit of the probability of occurrence of the heat and drought extremes from 2019, the annual expected damage value is €185 million. If the probability of occurrence increases by a factor of 10 (to 10 years), the annual expected damage value is €1.85 billion, which would correspond to a climate change-related increase of €1.67 billion (90% of the total damage). Assuming a return period every 300 years (the lower limit of occurrence probability according to the WWA), the annual expected damage value for the event is about €62 million. Increasing the probability of occurrence by a factor of 10 leads to an annual expected damage value of €617 million (which would correspond to a climate change-related difference of €555 million). However, as a complete attribution of the 2018 heat waves for Germany has not yet been determined, this statement can only be made for the events of 2019 for the time being - consequently, further attribution and damage studies are necessary for a comprehensive picture.

Understanding the dynamics and impacts of climate change is crucial for policy making. Only what can be measured can be managed. Currently, there is a clear underrepresentation in economic loss and damage from droughts and heatwaves in Germany. This paper provides a comprehensive picture on the data on loss and damage and outlines a methodology to gauge their monetary magnitudes. It becomes clear that this blind spot is associated with a substantial price tag. However, further work on the impacts of heatwaves and droughts is needed. Major blind spots, such as the loss and damage from biodiversity loss, remain. The numbers presented in the study merely reflect a lower bound estimate. Still, considering the progressing climate change, the numbers point to a clear call of action. A broader and more systemic climate mitigation action in combination with climate adaptation can avoid further loss and damage in the coming decades and centuries.

Sources

an der Heiden, M., Muthers, S., Niemann, H., Buchholz, U., Grabenhenrich, L., & Matzarakis, A. (2020). Heat-Related Mortality: An Analysis of the Impact of Heatwaves in Germany Between 1992 and 2017. *Deutsches Ärzteblatt International, 117*(37), 603-609. doi:10.3238/arztebl.2020.0603

Axnick, M.(Heat-related mortality in Berlin and Brandenburg) Hitzebedingte Sterblichkeit in Berlin und Brandenburg. *Zeitschrift Für Amtliche Statistik in Berlin Und Brandenburg,* (1/2021), 34-39. Retrieved from https://download.statistik-berlin-brandenburg.de/4c241e5c83eedf6b/d9ec6a993297/hz_202101-06.pdf

Beck, W. (2010). (Effects of drought and heat on forest condition in Germany - forest growth results of the study commissioned by BMELV) Auswirkungen von Trockenheit und Hitze auf den Waldzustand in Deutschland - waldwachstumskundliche Ergebnisse der Studie im Auftrag des BMELV. In J. Nagel (Ed.), *Beiträge / Deutscher Verband Forstlicher Forschungsanstalten, Sektion Ertragskunde: Jahrestagung 17. - 19. Mai 2010, Körbecke am Möhnesee* (pp. 56-65) Deutscher Verband Forstlicher Forschungsanstalten, Sektion Ertragskunde.

Bettgenhäuser, K., Boermans, T., Offermann, M., Krechting, A., Becker, D., Kahles, M., (Eds.). (2011). *(Climate protection through reduction of energy demand for building cooling) Klimaschutz durch Reduzierung des Energiebedarfs für Gebäudekühlung.* Retrieved from http://www.uba.de/uba-info-medien/3979.html

Bissolli, P., Deutschländer, T., Imbery, F., Haeseler, S., Lefebvre, C., Blahak, J., Schreiber, K. (2019). *(Heatwave July 2019 in Western Europe - new national record in Germany. Report of the German Weather Service) Hitzewelle Juli 2019 in Westeuropa – neuer nationaler Rekord in Deutschland. Bericht des Deutschen Wetterdiensts.* Deutscher Wetterdienst. Retrieved from https://www.dwd.de/DE/leistungen/besondereereignisse/temperatur/20190801_hitzerekord_juli2019.html

Bundesministerium für Ernährung und Landwirtschaft. (2017). *(Extreme weather in agriculture and forestry: Measures for prevention and loss adjustment) Extremwetterlagen in der Land- und Forstwirtschaft: Maßnahmen zur Prävention und Schadensregulierung.* Retrieved from https://web.archive.org/web/20181104213242/http://www.bmel.de/SharedDocs/Downloads/Broschueren/Extremwetterlagen.pdf?__blob=publicationFile

Bundesministerium für Ernährung und Landwirtschaft. (2019). *(Economic accounts for agriculture 2018: Production of the agricultural industry 2018) Landwirtschaftliche Gesamtrechnung 2018: Erzeugung des landwirtschaftlichen Wirtschaftsbereichs 2018.* Retrieved from https://www.bmel-statistik.de/fileadmin/daten/SGB-0100022-2018.pdf

Bundesministerium des Innern und für Heimat, & Bundesministerium der Finanzen. (2022). *(2021 Flood Report: Disaster Relief, Reconstruction, and Evaluation Processes) Bericht zur Hochwasserkatastrophe 2021: Katastrophenhilfe, Wiederaufbau und Evaluierungsprozesse.* Retrieved from https://www.bmi.bund.de/SharedDocs/downloads/DE/veroeffentlichungen/2022/abschlussbericht-hochwasserkatastrophe.html

Bux, K. (2006). *(Climate in the workplace. Status of occupational science findings - needs analysis for further research) Klima am Arbeitsplatz. Stand arbeitswissenschaftlicher Erkenntnisse - Bedarfsanalyse für weitere Forschungen.* Dortmund: Bundesanstalt für Arbeitsschutz und Arbeitsmedizin. Retrieved from https://www.baua.de/DE/Angebote/Publikationen/Berichte/Gd45.pdf

Deutscher Wetterdienst. (2019). *(Germany weather in summer 2019: Sunny and low precipitation - new temperature records) Deutschlandwetter im Sommer 2019: Sonnenscheinreich und niederschlagsarm – neue Temperaturrekorde.* Retrieved from https://www.dwd.de/DE/presse/pressemitteilungen/DE/2019/20190830_deutschlandwetter_sommer2019.pdf?__blob=publicationFile&v=2

Diersen, M. A., Taylor, G., & May, A. (2002). Direct and Indirect Effects of Drought on South Dakota's Economy. *Economics Commentator. Economics Department, South Dakota State University,* (432) Retrieved from https://openprairie.sdstate.edu/econ_comm/423/

Elsasser, P., Altenbrunn, K., Köthke, M., Lorenz, M., & Meyerhoff, J. (2021). *(Regionalized assessment of forest services in Germany) Regionalisierte Bewertung der Waldleistungen in Deutschland.* (No. 79).Bundesministerium für Ernährung und Landwirtschaft. Retrieved from https://www.thuenen.de/media/publikationen/thuenen-report/Thuenen_Report_79.pdf

García-Herrera, R., Garrido-Perez, J., Barriopedro, D., Ordonez, C., Vicente-Serrano, S., Nieto, R., Yiou, P. (2019). The European 2016/17 Drought. *Journal of Climate, 32*(11), 3169-3187. doi:10.1175/JCLI-D-18-0331.1

Gesamtverband der Deutschen Versicherungswirtschaft e.V. (2020). *(Natural Hazards Report 2020: The Loss and Damages Chronicle of German Insurers) Naturgefahrenreport 2020. Die Schaden-Chronik der deutschen Versicherer.* Gesamtverband der Deutschen Versicherungswirtschaft e.V. (GDV). Retrieved from https://www.gdv.de/resource/blob/63610/9fb7d9d95fa0874f312ae871363310fa/naturgefahrenreport-2020---schadenchronik-data.pdf

Gesamtverband der Deutschen Versicherungswirtschaft e.V. (2016). *(Agricultural multi-risk insurance for Germany) Landwirtschaftliche Mehrgefahrenversicherung für Deutschland.* Gesamtverband der Deutschen Versicherungswirtschaft e.V. (GDV). Retrieved from https://vereinigte-hagel.net/de/wp-content/uploads/GDV_Sonderheft_Landwirtschaftliche-Mehrgefahrenversicherung-fuer-Deutschland.pdf

Hirschfeld, J., Schulze, N., & Hock, A. (2021). *(Prioritization of individual damage and cost dimensions of climate change impacts: Brief study within the project "Kosten durch Klimawandelfolgen in Deutschland") Priorisierung einzelner Schadens- und Kostendimensionen der Folgen des Klimawandels: Kurzstudie im Rahmen des Projektes Kosten durch Klimawandelfolgen in Deutschland.* Institut für ökologische Wirtschaftsforschung (IÖW). Retrieved from https://www.ioew.de/fileadmin/user_upload/DOKUMENTE/Publikationen/2021/Hirschfeld_et_al_2021_Priorisierung_einzelner_Schadens-_und_Kostendimensionen_der_Folgen_des_Klimawandels.pdf

Imbery, F., Friedrich, K., Koppe, C., Janssen, W., Pfeifroth, U., Daßler, J., & Bissolli, P. (2018). *(2018 warmest summer in northern and eastern Germany. German Weather Service. Research report of the departments for climate monitoring, hydrometeorology and agro-meteorology) 2018 wärmster Sommer im Norden und Osten Deutschlands. Deutscher Wetter-dienst.*

Forschungsbericht der Abteilungen für Klimaüberwachung, Hydrometeorologie und Agrar-meteorologie. Deutscher Wetterdienst. Retrieved from https://www.dwd.de/DE/leistungen/besondereereignisse/temperatur/20180906_waermstersommer_nordenosten2018.pdf?__blob=publicationFile&v=7

Imbery, F., Friedrich, K., Fleckenstein, R., Kaspar, F., Bissolli, P., Daßler, J., & Haeseler, S. (2019). *(New record June mean temperature for Germany and intense heat wave in Europe) Neuer Rekord der mittleren Junitemperatur für Deutschland und intensive Hitzewelle in Europa.* Deutscher Wetterdienst. Retrieved from https://www.dwd.de/DE/leistungen/besondereereignisse/temperatur/20190703_bericht_juni2019.html

International Energy Agency. (2018). *The Future of Cooling: Opportunities for energy-efficient air conditioning*. Paris: International Energy Agency (IEA). Retrieved from https://iea.blob.core.windows.net/assets/0bb45525-277f-4c9c-8d0c-9c0cb5e7d525/The_Future_of_Cooling.pdf

Kahlenborn, W., Porst, L., Voß, M., Fritsch, U., Renner, K., Zebisch, M., Schauser, I. (2021). *(Climate Impact and Risk Analysis for Germany 2021. Executive summary) Klimawirkungs- und Risikoanalyse 2021 für Deutschland. Kurzfassung.* (No. 26/2021).Umweltbundesamtes. Retrieved from https://www.umweltbundesamt.de/publikationen/KWRA-Zusammenfassung

Landwirtschaftskammer Österreich. (2021). *(Indicative prices for the sale of silage corn from field 2021) Richtpreise für den Verkauf von Silomais ab Feld 2021*. Retrieved from https://www.lko.at/richtpreise-f%C3%BCr-den-verkauf-von-silomais-ab-feld-2021+2400+3472277

Kaspar, F., Friedrich, K., & Imbery, F. (2020). *(2019 globally second warmest year: Temperature development in Germany in a global context) 2019 global zweitwärmstes Jahr: Temperaturentwicklung in Deutschland im globalen Kontext.* Deutscher Wetterdienst. Retrieved from https://www.dwd.de/DE/leistungen/besondereereignisse/temperatur/20200128_vergleich_de_global.html

Kjellstrom, T., Briggs, D., Freyberg, C., Lemke, B., Otto, M., & Hyatt, O. (2016). Heat, Human Performance, and Occupational Health: A Key Issue for the Assessment of Global Climate Change Impacts. *Annual Review of Public Health, 37*(1), 97-112. doi:10.1146/annurev-publhealth-032315-021740

Hübler, M., Klepper, G., & Peterson, S. (2007). Costs of climate change: The effects of rising temperatures on health and productivity in Germany. *Kiel Working Paper No. 1321.*

Kreienkamp, F., Philip, S. Y., Tradowsky, J. S., Kew, S. F., Lorenz, P., Arrighi, J., Wanders, N. (2021). *Rapid attribution of heavy rainfall events leading to the severe flooding in Western Europe during July 2021.*UGent. Retrieved from http://hdl.handle.net/1854/LU-8732135

Martin-Ortega J., Gonzalez-Eguino, M., & Markandya, A. (2012). The costs of drought: the 2007/2008 case of Barcelona. *Water Policy, 14*(3), 539-560. doi:10.2166/wp.2011.121

Matthey, A., & Bünger, B. (2020). *(Methodological Convention 3.1 for the determination of environmental costs. Cost rates) Methodenkonvention 3.1 zur Ermittlung von Umweltkosten. Kostensätze.* Dessau-Roßlau: Umweltbundesamt. Retrieved from https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-12-21_methodenkonvention_3_1_kostensaetze.pdf

Meinert, T., Becker, A., Bissolli, P., Daßler, J., Breidenbach, J. N., & Ziese, M. (2019). *(Causes and consequences of drought in Germany and Europe as of June 2019) Ursachen und Folgen der Trockenheit in Deutschland und Europa ab Juni 2019. Forschungsbericht der Abteilungen Klimaüberwachung, Agrar- und Hydrometeorologie.* Deutscher Wetterdienst. Retrieved from https://www.dwd.de/DE/leistungen/besondereereignisse/duerre/20190712_trockenheit_juni_juli_2019.html

Möhring, B., Bitter, A., Bub, G., Dieter, M., Dög, M., Hanewinkel, M., Thoma, F. (2021). *(Estimation of the economic damages of the extreme weather events of the years 2018-2020 in the forestry sector) Abschätzung der ökonomischen Schäden der Extremwetterereignisse der Jahre 2018-2020 in der Forstwirtschaft.* Berlin: Deutschen Forstwirtschaftsrates. Retrieved from https://dfwr.de/wp-content/uploads/2022/01/DFWR-Position-Schaeden-Fowi-Langfassung-Studie.pdf

Mühr, B., Kubisch, S., Marx, A., Guth, J., Wisotzky, C., Latt, C., Kunz, M. (2018). *(Drought & Heatwave Summer 2018 (Germany)) Dürre & Hitzewelle Sommer 2018 (Deutschland).* CEDIM Forensic Disaster Analysis. Retrieved from https://www.cedim.kit.edu/download/FDA_Duerre_Hitzewelle_Deutschland_report1_final.pdf

Ní Dhubháin, Á, Fléchard, M., Moloney, R., & O'Connor, D. (2009). Assessing the value of forestry to the Irish economy — An input–output approach. *Forest Policy and Economics, 11*(1), 50-55. doi:10.1016/j.forpol.2008.08.005

Pissarskoi, E., v. Möllendorff, C., & Sterba, M. (2015). *(Estimation of Costs and Benefits of Adaptation to Heat Events: Case Study for the City of Cologne) Abschätzung von Kosten und Nutzen der Anpassung an Hitzeereignisse: Fallstudie für die Stadt Köln.* Berlin: Institut für ökologische Wirtschaftsforschung GmbH. Retrieved from http://www.oekonomie-klimawandel.de/data/oekl/user_upload/Dateien/KNA_Hitze_Koeln_VorgehenErgebnisse_final.pdf

Scheele, M. (2018). (On dry land) Auf dem Trockenen. *GDV Gesamtverband Der Versicherer E.V.,* Retrieved from https://www.gdv.de/gdv/themen/klima/auf-dem-trockenen-39884

Seppänen, O., Fisk, W., & Faulkner, D. (2004). Control of Temperature for Health and Productivity in Offices. *Lawrence Berkeley National Laboratory, 111*, 680-686. Retrieved from http://escholarship.org/uc/item/39s1m92c

Sieg, T., Schinko, T., Vogel, K., Mechler, R., Merz, B., & Kreibich, H. (2019). Integrated assessment of short-term direct and indirect economic flood impacts including uncertainty quantification. *PloS One, 14*(4), e0212932. doi:10.1371/journal.pone.0212932

Statistisches Bundesamt (Destatis). (2020). *(Correction: Drought damages the forest: Damaged wood felling caused by insect infestation almost tripled in 2019 compared to the previous year) Korrektur: Trockenheit schadet dem Wald: Durch Insektenbefall verursachter Schadholzeinschlag 2019 im Vergleich zum Vorjahr fast verdreifacht.*

Trenczek, J., Lühr, O., Eiserbeck, L., & Leuschner, V. (2022). *(Project Report "Kosten durch Klimawandelfolgen": Losses of Flash Floods and Floods in July 2021 in Germany: An ex-post Analysis) Projektbericht „Kosten durch Klimawandelfolgen“: Schäden der Sturzfluten und Überschwemmungen im Juli 2021 in Deutschland: Eine ex-post-Analyse.* Düsseldorf: Prognos AG. Retrieved from https://www.prognos.com/sites/default/files/2022-07/Prognos_Klimawandelfolgen-Deutschland_Detailuntersuchung%20Flut_AP2_3b_.pdf

Umweltbundesamt. (2018). *(Indicators for the German Adaptation Strategy Indicator Fact Sheets for the Field of Action Forest and Forestry) Indikatoren für die Deutsche Anpassungsstrategie Indikator-Factsheets zum Handlungsfeld Wald und Forstwirtschaft.* Retrieved from https://www.umweltbundesamt.de/sites/default/files/medien/4770/dokumente/fw-i-5_indikator_schadholz_buchdrucker_2019.pdf

Vautard, R., van Aalst, M., Boucher, O., Drouin, A., Haustein, K., Kreienkamp, F., Wehner, M. (2019). *Human contribution to the record-breaking June and July 2019 heatwaves in Western Europe.* World Weather Attribution. Retrieved from https://www.worldweatherattribution.org/wp-content/uploads/July2019heatwave.pdf

Watts, N., Amann, M., Arnell, N., Ayeb-Karlsson, S., Beagley, J., Belesova, K., Costello, A. (2021). The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises. *The Lancet (British Edition), 397*(10269), 129-170. doi:10.1016/S0140-6736(20)32290-X

Winklmayr, C., Muthers, S., Niemann, H., Mücke, H., & an der Heiden, M. (2022). Heat-related mortality in Germany from 1992 to 2021. *Deutsches Ärzteblatt International, 119*(26), 451-457. doi:10.3238/arztebl.m2022.0202

Wittwer, G., Madden, J. R., & Horridge, J. M. (2003). *Using a highly disaggregated multi-regional single-country model to analyse the impacts of the 2002-03 drought on Australia.* Retrieved from http://econpapers.repec.org/paper/copwpaper/g-141.htm

World Weather Attribution. (2018). Heatwave in northern Europe, summer 2018. *World Weather Attribution (WWA).* Retrieved from https://www.worldweatherattribution.org/attribution-of-the-2018-heat-in-northern-europe/

Annex

Table 5: Factor range in the 90% confidence interval for the computation of the indirect effects

Sector	Range of indirect effects
Agriculture, Forestry and Fisheries	0.6 – 0.85
Mining and quarrying	0.84 – 1.11
Manufacturing	1.53 – 2.39
Electricity, gas, steam and air conditioning supply	0.34 – 0.44
Water supply, sewerage, waste management and remediation activities	0.12 – 0.17
Construction	0.84 – 1.11
Wholesale, retail trade and repair of motor vehicles	0.68 – 0.96
Transportation and storage	0.36 – 0.46
Hotels and restaurants	0.54 – 0.91
Information and communication activities	0.61 – 0.85
Finance and insurance activities	0.65 – 1.24
Real estate activities	0.65 – 1.24
Professional, scientific and technical activities	0.48 – 0.63
Administrative and support service activities	0.32 – 0.51
Public administration, defence and obligatory social security	0.15 – 0.26
Education	0.24 – 0.45
Human health and social work activities	0.22 – 0.35
Arts, entertainment and recreation activities	0.44 – 0.80
Other service activities	0.32 – 0.51

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Table 6: Yields per hectare, harvest yields, sales prices, and revenue of selected crops until 2019

Crop type	Yields per hectare in dt			Harvest yield in 1,000t			Sales price in € per 100 kg			Revenue in 1,000€		
	2013-2017	2018	2019	2013-2017	2018	2019	2013-2017	2018	2019	2013-2017	2018	2019
Wheat	80.0	66.7	74.0	25,661	20,250	23,073	16.5	16.8	16.7	4,478,078	3,410,120	3,850,917
Rye and maslin	56.8	42.1	50.9	3,589	2,202	3,237	13.9	16.0	15.1	588,203	352,073	490,118
Barley	69.5	57.7	67.8	11,027	9,590	11,587	12.8	16.6	15.7	1,377,664	1,587,102	1,818,003
Oats	47.0	41.1	41.1	587	575	518	15.3	15.5	16.3	105,013	89,072	84,567
Mixed grain	43.6	37.4	35.8	59	41	32	16.5	16.8	16.7	15,386	6,928	5,378
Triticale	64.3	54.1	61.3	2,579	1,937	2,195	14.9	16.0	15.6	415,590	309,497	343,226
Grain maize/Maize to complete maturing (incl. Corn-Cob-Mix)	97.5	81.4	88.1	4,442	3,346	3,665	16.5	16.5	16.5	826,991	552,014	605,451
Peas	34.9	27.9	30.6	230	198	230	193.1	229.5	218.5	382,294	454,636	501,458
Field beans	39.0	29.1	32.5	125	160	159	112.5	134.8	121.4	110,203	215,763	193,250
Sweet lupin	17.1	9.5	12.2	43	22	26	193.1	229.5	218.5	73,196	50,148	55,980
Soybeans	27.9	24.4	29.1	28	59	84	33.7	33.7	33.0	9,342	19,735	27,849
Potatoes	444.5	353.8	390.3	10,834	8,916	10,616	17.7	16.9	24.3	1,790,052	1,508,547	2,575,480
Sugar beets	741.2	632.8	727.4	26,552	26,198	29,751	2.9	2.6	2.7	753,244	681,146	803,565
Rape and turnip rape	38.1	29.9	33.0	5,182	3,672	2,828	36.2	35.3	35.9	1,981,010	1,296,117	1,013,874
Sunflowers	21.3	18.2	20.5	41	36	45	29.6	31.5	33.7	13,339	11,451	15,212
Silage maize/green maize	436.4	352.9	390.0	91,111	77,497	86,697	2.893	2.888	2.891	2,772,333	2,237,721	2,506,410
Cereals for whole plant harvest	269.7	229.5	285.5	2,488	1,997	3,312	16.5	16.8	16.7	375,618	336,236	552,739
Total				343,179	278,771	319,917				35,917,955	29,797,877	34,491,500

Own calculation andrepresentation, Data source: Statistisches Bundesamt: Fachserie 3, R 3.2.1, Feldfrüchte 2020 and Eurostat: Selling prices of agricultural products (absolute prices) 2021. Individual sales prices were calculated based on market developments or similar goods (e.g., silage corn) or estimated due to a lack of statistical data. The prices per unit of weight are based on the dry weights of the products.

Table 7: Damaged wood statistics for 2018 and 2019

Tree/ wood species group	Damaged wood according to the BMEL-country survey (Stand 30.09.2020)		Total	minus the forest area with usage restrictions	minus non-utilized solid wood	minus non-recovered quantity of damaged wood	Felling/recovery of damaged wood
	All figures in m³						
	2018	**2019**			**2018-2019**		
Oak	598,511	627,820	1,226,331	1,179,068	1,085,934	0	1,085,934
Beech	2,501,489	4,752,180	7,253,669	6,750,449	5,757,332	283,724	6,041,055
Spruce	27,036,700	57,857,701	84,894,401	79,323,173	60,799,422	15,286,745	76,086,167
Pine	5,473,300	5,482,299	10,955,599	10,315,869	8,360,337	1,654,526	10,014,863
Total	**35,610,000**	**68,720,000**	**104,380,000**	**97,589,044**	**76,038,131**	**17,210,375**	**93,248,505**

Own calculation based on Möhring et al. (2021). Assumption: deduction due to utilization constraints, unutilized solid wood and unprocessed damaged wood per year proportional to the amount of damaged wood from 2018 to 2020.

Table 8: Estimated calamity-related losses in revenue and incremental cost of recovery of damaged wood

Tree/ wood species group	Felling of damaged wood 2018-2019 (excl. non-recovered damaged wood)	Avg. wood revenue per m³	Revenue deduction due to calamity	Loss in revenue from recovery of damaged wood	normal wood harvesting costs	Cost surcharge for calamity	Incremental costs of recovery of damaged wood
	Mio. m³	€/m³	%	Mio. €	€/m³	%	Mio. €
Oak	1.1	75.6	10%	8	26.00	15%	4
Beech	5.8	48.35	20%	56	26.00	15%	22
Spruce	60.8	67.15	45%	1.837	26.00	15%	237
Pine	8.4	52.67	20%	88	26.00	15%	33
Total	**76.0**			**1.989**			**296**

Own calculation based on Möhring et al. (2021).

Table 9: Loss due to immaturity in forestry

Tree/ wood species group	Volume of damaged wood 2018-2019*	Wood stock older than 60 years	calculated calamity area	median relative yield class	standard end use age	value at age of cultivation	Cultural costs	Reference age (75% of the cultivation age)	age factor	Stock value at reference age	relation of age value at reference age to standard end use age	output value at reference age, derived from value	value of immaturity at reference age	Losses due to immaturity
	Mio. m³	m³/ha	ha		years	€/ha	€/ha	Alter		€/ha		€/ha	€/ha	Mio. €
Oak	1.2	269	4,383	I,7	180	35,920	13,495	135	0.854	32,646	0.574	20,634	12,012	53
Beech	6.8	334	20,211	I,9	140	18,685	4,137	105	0.857	16,605	0.548	10,243	6,362	129
Spruce	79.3	461	172,068	I,1	100	37,503	2,969	75	0.822	31,356	0.672	25,220	6,136	1,056
Pine	10.3	272	37,926	I,5	120	16,664	4,414	90	0.85	14,827	0.727	12,120	2,707	103
Total	97.6		234,588											**1,340**

Own calculation based on data of Möhring et al. (2021). Note: * excl. forest area with usage constraints

Table 10: Loss of revenue due to deductions from damaged wood

Tree/ wood species group	Non-recovered damaged wood	revenue after deducting harvesting costs	amount of damage of non-recovered damaged wood
	Mio. m³	€/m³	Mio. €
Oak	0.0	49.6	0
Beech	0.3	22.35	6
Spruce	15.3	41.15	629
Pine	1.7	26.67	44
Total	**76.0**		**680**

Own calculation based on Möhring et al. (2021). Assumption: Wood remains in the forest without additional costs.

Table 11: Estimated incremental costs for reforestation of the calamity area

Tree/ wood species group	Cost of natural regeneration	Cost of planting, average conditions	Share of regeneration type		normal cultural costs, weighted by regeneration type	Cost of planting, difficult conditions	assumed natural regeneration	Cost of post-calamity reforestation	Incremental cost of reforestation
			Planting	natural regeneration					
	€/ha	€/ha	%	%	€/ha	€/ha	%	€/ha	€/ha
Oak	2,600	16,500	46%	54%	8,930	18,900	20%	15,640	6,710
Beech	1,800	8,800	13%	87%	2,715	11,000	20%	9,160	6,445
Spruce	1,300	3,600	13%	87%	1,605	4,400	20%	3,780	2,175
Pine	1,900	5,800	16%	84%	2,527	7,500	20%	6,380	3,853
average of tree species	**1,900**	**8,675**			**3,944**	**10,450**		**8,740**	**4,796**
						Calamity area (ha)			**167,967**
						Additional costs in calamity areas (€ Mio.)			**806**

Own calculation based on Möhring et al. (2021). Since nationwide data on the tree species change i.e., the tree species proportions to be re-established on the calamity areas are lacking, but a significant increase in hardwood proportions is expected, the arithmetic mean value of the four tree species groups (amounting to €4,796/ha) is used in the calculation of the additional costs.

Table 12: Evaluated loss of increment 2018-2019

Tree/ wood species group	Total	minus the calamity area 2018-2020	minus the forest area with usage restrictions	loss of increment, 2003 (duration of 4 years)	2018-2019 X-times loss of increment compared to 2003	Total	minus share of non-utilized solid wood	avg. contribution margin (harvest cost-free wood revenue)	Loss in value-added
	wood growth BWI 2002-2012			*loss in increment 2018-2020*					
	Mio. m³	Mio. m³	Mio. m³			Mio. m³	Mio. m³	€/ m³	Mio. €
Oak	7.2	7.2	6.7	13.1%	17.0%	1.1	1.1	49.6	52
Beech	26.4	26.2	24.5	64.8%	84.2%	20.6	18.5	22.34	413
Spruce	41.3	37.5	35.0	119.1%	154.8%	54.2	52.0	41.14	2,138
Pine	20.7	20.3	19.0	64.2%	83.5%	15.8	15.4	26.67	410
Total	95.7	91.1	85.2			91.8	86.9		**3,013.5**

Own calculation based on Möhring et al. (2021). Estimated as 1.3 times the loss of increment of the drought year of 2003, from Beck (2010), evaluated with the mean profit contribution in €/fm according to TBN-Forst of the years 2012-2017.

Table 13: Tree species-specific substitution factors

Tree species group	Oak	Beech	Spruce	Pine
Substitution factor	0,82	0,77	0,79	0,84

Elsasser et al. (2021)

Table 14: Distribution of damages due to heat-related productivity losses

	2018		2019		
Sector	**non-adaptation factor**	**direct damages**	**non-adaptation factor**	**directe damages**	**direct total damages**
Agriculture, Forestry and Fisheries	100%	48.76	100%	39.60	88.35
Mining and quarrying	100%	8.46	100%	6.82	15.29
Manufacturing	61.1%	668.07	60.4%	553.23	1,221.30
Electricity, gas, steam and air conditioning supply	61.1%	28.20	60.4%	24.11	52.31
Water supply, sewerage, waste management and remediation activities	61.1%	19.78	60.4%	16.90	36.68
Construction	100%	294.93	100%	247.19	542.11
Wholesale, retail trade and repair of motor vehicles	61.1%	53.41	60.4%	44.98	98.39
Transportation and storage	29.2%	207.63	28.0 %	166.61	374.24
Hotels and restaurants	61.1%	58.41	60.4%	49.08	107.49
Information and communication activities	39.8%	92.25	38.8%	78.60	170.85
Finance and insurance activities	39.8%	77.55	38.8%	61.78	139.34
Real estate activities	39.8%	21.45	38.8%	17.62	39.07
Professional, scientific and technical activities	39.8%	166.26	38.8%	138.06	304.32
Administrative and support service activities	39.8%	105.63	38.8%	84.68	190.31
Public administration, defence and obligatory social security	39.8%	123.50	38.8%	102.33	225.83
Education	61.1%	143.74	60.4%	121.18	264.92
Human health and social work activities	61.1%	452.74	60.4%	383.68	836.43
Arts, entertainment and recreation activities	61.1%	34.73	60.4%	29.38	64.11
Other service activities	61.1%	121.58	60.4%	101.59	223.17
Total		**2,727.07**		**2,267.41**	**4,994.49**

Own calculation. Data source: destatis, DWD, IEA, Prognos Economic Outlook
All figures in € million

Table 15: Computation of indirect effects of heat-related productivity losses

Sector	Range of indirect effects	Amount of indirect damages, 2018 in € millions		Amount of indirect damages, 2019 in € millions	
Agriculture, Forestry and Fisheries	0.6 – 0.85	29.3	41.4	23.8	33.7
Mining and quarrying	0.84 – 1.11	7.1	9.4	5.8	7.6
Manufacturing	1.53 – 2.39	1,020.5	1,593.7	845.1	1,319.7
Electricity, gas, steam and air conditioning supply	0.34 – 0.44	9.6	12.5	8.2	10.7
Water supply, sewerage, waste management and remediation activities	0.12 – 0.17	2.3	3.4	2.0	2.9
Construction	0.84 – 1.11	248.8	328.1	208.5	275.0
Wholesale, retail trade and repair of motor vehicles	0.68 – 0.96	36.4	51.3	30.6	43.2
Transportation and storage	0.36 – 0.46	75.2	94.6	60.3	75.9
Hotels and restaurants	0.54 – 0.91	31.5	53.2	26.5	44.7
Information and communication activities	0.61 – 0.85	56.2	78.7	47.9	67.1
Finance and insurance activities	0.65 – 1.24	50.2	96.2	40.0	76.6
Real estate activities	0.65 – 1.24	13.9	26.6	11.4	21.9
Professional, scientific and technical activities	0.48 – 0.63	80.4	104.4	66.8	86.7
Administrative and support service activities	0.32 – 0.51	33.7	54.0	27.0	43.3
Public administration, defence and obligatory social security	0.15 – 0.26	18.5	31.9	15.4	26.4
Education	0.24 – 0.45	35.1	64.1	29.6	54.1
Human health and social work activities	0.22 – 0.35	99.8	159.7	84.5	135.4
Arts, entertainment, and recreation activities	0.44 – 0.8	15.2	27.9	12.9	23.6
Other service activities	0.32 – 0.51	38.7	62.1	32.4	51.9
Total		**1,902.3**	**2,893.4**	**1,578.5**	**2,400.4**

Own calculation. Data source: Sieg et al, 2019. In individual cases, the indirect shares were derived from additional secondary sources or based on similar economic sectors.
All figures in € million