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Quantifying heat vs. drought-induced yield decline of German cropping systems and the mitigating potential of irrigation

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1 Abstract

Accurately quantifying crop yield reductions from heat and drought stress is essential for predicting how a changing climate will impact future crop production. Here, we assess the relative contributions of heat and drought stress on crop yield losses across Germany using the process-based ecosystem model LandscapeDNDC.

This is achieved via a two-step calibration process, in which key model parameters governing the growth of wheat and maize (the two major crops in Germany) are optimised to simulate crop yields in both stressed and unstressed conditions. We show that recent yield losses in Germany were predominantly caused by drought stress, with heat stress playing only a negligible role. Consequently, yield losses could have been largely eliminated through irrigation, with an average of 156 ± 60 mm of water in 2018 across Germany necessary. We show that irrigation demand increases exponentially with decreasing plant-available water, indicating that the importance of this mitigation measure will grow under future climate conditions.

The models' ability to accurately capture the consequences of recent extreme climatic events on crop yields makes it a suitable candidate for evaluating the implications of climate change on both crop production and, more generally, on the carbon, nitrogen and water cycles of cropping systems in Central Europe.

Keywords: Germany, heat stress, drought stress, irrigation, extreme events Submitted to: *Environ. Res. Lett.*

2 Introduction

Crop susceptibility to extreme events is a major concern for future food stability (Asseng et al., 2015; Baruth et al., 2022) and remains an important topic regarding the vulnerability of the global food system (Li et al., 2026). Central Europe has experienced increasing climatic extremes affecting crop yields, notably the severe 2018 drought, where cereal production fell 25% below average, making it "the worst harvest of the century" (Mühr et al., 2018; Stürzenhofecker and Zacharakis, 2018). Across central Europe, extreme droughts are projected to become more frequent with ongoing climate change (Balting et al., 2021; Han et al., 2026; Hoegh-Guldberg et al., 2018; Ionita et al., 2022), and the risk of compound heat-drought events is also increasing (Lesk et al., 2022), further exacerbating crop yield declines (Bheemanahalli et al., 2022; Cohen et al., 2021).

Existing studies attempting to disentangle yield reduction drivers in Germany often rely on statistical models linking yield anomalies to precipitation or temperature (Becker et al., 2025; Bogenreuther et al., 2025; Lüttger and Feike, 2018; Peichl et al., 2019; Rezaei et al., 2015; Webber et al., 2020). However, statistical approaches struggle to separate intimately linked heat and drought effects. Despite their mechanistic basis, process-based crop models remain subject to uncertainties in model structure, parameterisation, and management inputs, particularly when simulating crop responses to extreme climatic events. Often, the impacts of extreme events such as heat waves and droughts are still underestimated in mechanistic models, especially if applied at larger scales (Auer et al., 2026; Heinicke et al., 2022). Therefore, most analyses call for models better equipped for taking up the challenges of modelling extreme events (Heinicke et al., 2022; Maiorano et al., 2017), as improved process understanding makes them better suited to predicting the impacts of future climates than data-driven approaches (Hu et al., 2024). Consequently, the relative importance of heat and drought stress for yield losses in Germany remains insufficiently quantified at the national scale.

Understanding the dominant drivers is essential for designing adaptation measures. In Germany, where agriculture is predominantly rain-fed (Destatis, 2022), irrigation represents a critical resilience strategy (Santini et al., 2025), yet the amount of irrigation required to offset drought-related losses and its relationship to drought severity remain poorly quantified.

In this study, we address the resulting questions: (i) Can a process-based ecosystem model reproduce the observed spatial and temporal variability in German crop yields during recent drought-affected years? (ii) What were the relative contributions of heat and drought stress on crop yield losses during the sequence of extreme years from 2018 to 2022? And (iii) To what extent could irrigation mitigate drought-induced yield losses, and how does this demand change with drought severity?

To address these questions, we first apply the calibrated LandscapeDNDC model to district-level yield data and evaluate its ability to reproduce spatial heterogeneity and interannual variability across Germany. Using counterfactual simulations, we then isolate the effects of individual abiotic stress factors and quantify their contributions to observed yield losses. Finally, simulations under an idealised irrigation scenario are used to assess the potential of irrigation to mitigate drought impacts and to estimate associated water requirements.

3 Methods

3.1 LandscapeDNDC Model

To simulate crop growth in Germany, we used the process-based biogeochemical model LandscapeDNDC (Haas et al., 2013). LandscapeDNDC simulates yields as well as carbon, nitrogen and water dynamics in the plant-soil system of terrestrial ecosystems. It has a modular setup, with different sub-modules for plant growth, soil biogeochemistry and water dynamics. We used revision 12212 of LandscapeDNDC with the module combination MeTr^X (Kraus et al., 2015), PlaMo^x (e.g. Petersen et al., 2021) for plant growth, WatercycleDNDC (Kiese et al., 2011) and CanopyECM (Grote et al., 2011) for microclimate.

Plant growth is divided into four plant compartments (stem, leaf, grain and roots), which are supplied by incoming carbon via photosynthesis, governed by the processes introduced by Ball et al. (1987) and Farquhar et al. (1980). Allocation among compartments is controlled by environmental constraints, including temperature, water availability, and nutrient status. Yield is determined by the plant biomass at harvest, which is linked to the grain carbon by a fixed factor.

Soil water dynamics are represented using a multilayer tipping-bucket approach, accounting for interception, evapotranspiration, infiltration, and percolation processes. Both Molina-

Herrera et al. (2016) and Houska et al. (2017) have shown the capabilities of WatercycleDNDC to accurately represent field conditions.

Crops investigated in this study and chosen for calibration were limited to maize (*Zea mays)* and wheat (*Triticum aestivum)* due to the high computational demand of each calibration. These crops are the most commonly grown in Germany, accounting for around 29 and 24 % of agriculturally used area, respectively (Blickensdörfer et al., 2022). Nevertheless, full crop rotations were considered, and other crops grown in rotation with maize and wheat were simulated with the default model parameters.

This study focuses on improving and evaluating the model's representation of physiological stress responses, in particular drought and heat stress, which are critical drivers of yield variability under recent extreme climatic conditions in Germany.

3.2 Representation of Abiotic Stresses in LandscapeDNDC

3.2.1 Impacts of heat and drought stress

LandscapeDNDC represents abiotic stresses via a combination of physiological limitations on growth and stress-induced damage processes. Direct drought and heat have an impact on the photosynthetic carboxylation velocity, stomatal conductance, leaf growth rates and allocation of carbon stocks (leaf vs stem). These responses act as temporary physiological limitations, allowing growth processes to resume under favourable conditions. Heat and drought stress can also accelerate plant senescence, with increasing stress severity causing a larger fraction of biomass to enter senescence. When both stresses occur simultaneously, senescence is determined by the dominant stress factor. Anthesis heat stress is treated separately and reduces grain-filling capacity of the plant through irreversible damage during the flowering period. Unlike the temporary physiological responses described above, these effects persist throughout the remainder of the growing season and can therefore result in lasting yield reductions.

These stress representations form the basis for attributing yield reductions to heat and drought processes and for evaluating their relative importance under extreme climate conditions. For details about the implementation, please refer to Supplementary Section S1.

3.2.2 Idealized irrigation as mitigation

Irrigation is applied as a threshold-based sprinkler irrigation. As soon as the plant-available water content falls below a critical threshold, irrigation is triggered, and sufficient water is supplied to bring the plant available soil water back above the threshold.

This implementation is designed to represent an idealised irrigation response and is used to quantify the potential of irrigation to mitigate drought-induced yield losses under current climatic conditions. By comparing irrigated and non-irrigated simulations, we estimate the effectiveness of irrigation as an adaptation measure.

3.2.3 Counterfactual Scenarios

In the counterfactual scenarios, select abiotic stresses are individually disabled for all model time steps, allowing crop growth to be unconstrained by the specific stress. Yield differences between the default and counterfactual simulations are attributed to the respective stress factor, thereby providing estimates of stress-specific yield losses. Some indirect influences remain in this approach, e.g. enhanced soil drying under elevated temperatures.

3.3 Calibration of LandscapeDNDC

We calibrated LandscapeDNDC against district-level yield data for 403 German districts, as reported by Duden et al. (2024). For each crop, 10 calibration districts were selected. We used a two-step calibration process: first for potential yield, then for stress. Model performance was evaluated using the root-relative mean squared error (RRMSE) between simulated and observed yields, which served as the objective function. In the first step, crop growth parameters were calibrated under low-stress conditions with abiotic stress factors disabled, allowing the model to be constrained primarily by crop growth and development processes. In the second step, stress-related parameters were introduced to capture yield variability under water and temperature limitations. This step builds on the previously calibrated potential yield setup and ensures that simulated stress responses are consistent with observed yield fluctuations across climatically contrasting districts.

The calibrated parameter sets were then used for national-scale simulations. Further details on the calibration dataset selection, parameter optimisation procedure, and ensemble construction are provided in the Supplementary Section S2.

3.4 Application of LandscapeDNDC on the national scale of Germany

The model was applied across Germany using a stratified point sampling approach: 50 sites per district were simulated in a novel framework integrating high-resolution inputs for soil, climate, and management (see Supplementary Section 1). We used a five-year spin-up period, and analysis was performed for the years 2017 to 2022. These years were chosen due to the availability of high-resolution management data, the striking severity of the drought and heat extremes found in these years (Beillouin et al., 2020), the compound nature of these events (Bevacqua et al., 2024) and their strong impact on German crop yields. We present results based on the combination of the best parameter sets identified during both calibration steps. To account for parameter uncertainty, sensitivity analysis was performed using an ensemble of the five best parameter sets from the stress calibration.

A set of counterfactual scenarios was run in which individual stress factors (i.e. drought, heat and anthesis-heat stress) were turned off one at a time. Climatic conditions remained unchanged, and specific results were then compared with the default simulation as a way of attributing yield declines to different stress factors.

Default runs assumed no irrigation due to the lack of spatial data. To evaluate the mitigation potential of irrigation, idealised irrigation scenarios were conducted. Irrigation was triggered when soil water deficits exceeded a critical threshold, alleviating drought stress to estimate the water requirements needed to restore yields. For technical details, see Supplementary Section S1.

4 Results

4.1 Model evaluation across Germany

Simulations of the 403 districts in Germany show that LandscapeDNDC can reproduce the magnitude and temporal variations of crop yields at both the national scale and district level (Figure 1). For Germany, the average reported yields in the period are 15.4 t/ha for maize and 6.39 t/ha for wheat, compared with simulated yields of 14.4 t/ha and 5.8 t/ha. Maize yields show significant annual variation at the national scale, which is well captured by the simulations, whereas wheat yields show lower interannual variability (Figure 1).

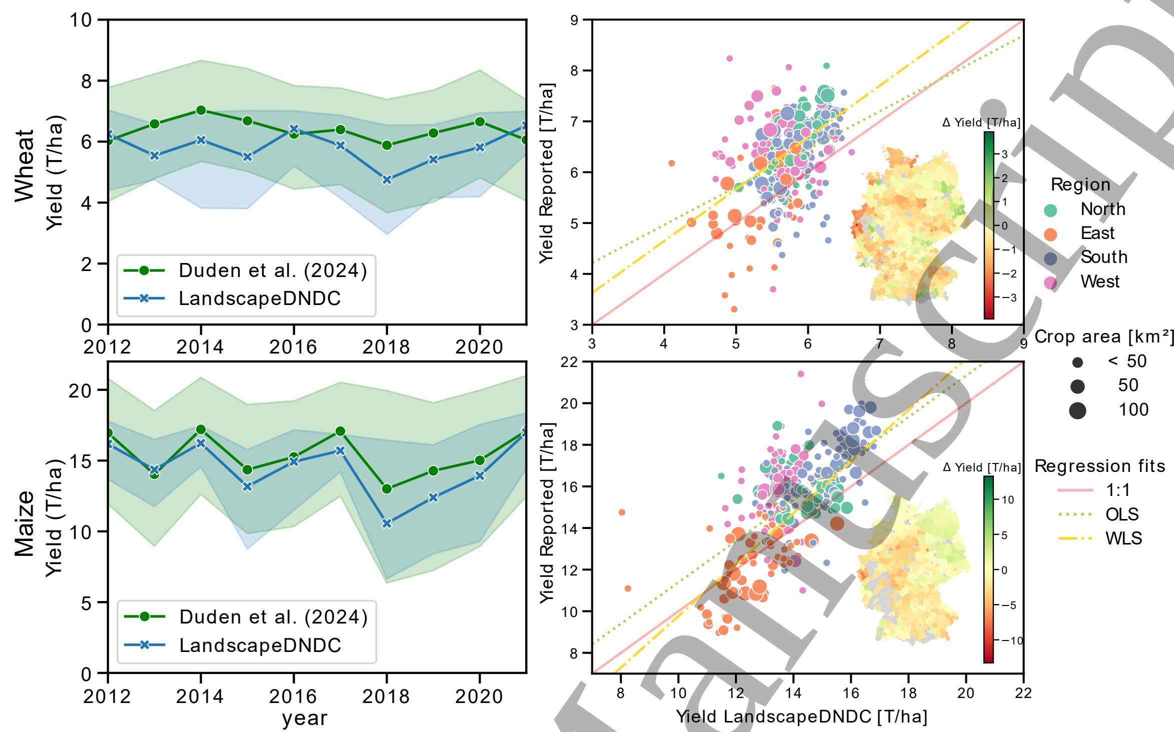


Figure 1: Comparison of harmonised reported (Duden et al. 2024) and simulated (LandscapeDNDC) wheat yields (top row) and maize biomass (bottom row). The left column shows yields averaged across Germany, with shading showing the 0.95 percentile of the district data. The right column shows a scatterplot of all the district yields reported (from Duden et al. 2024) and simulated via LandscapeDNDC. Data was aggregated over the 2017 – 2022 period with lines for Ordinary Least Squares (OLS) and Weighted Least Squares (WLS), with the map showing the district-wise differences between the two, with grey districts having no reported data (For yearly resolution, see Supplementary Material 11 and 12). Parameters of the WLS: for wheat: slope = 0.98, R^2 = 0.38. Parameters for maize: 1.2 and an R^2 of 0.5.

A comparison of district level yields shows a significant relationship ($p < 0.05$) between the model and the data for all years (2017 – 2021) and crops, except for silage maize in 2017. Area-weighted linear regression analysis results in R^2 values ranging between 0.27 and 0.68 for wheat in the years 2018 – 2021 and 0.5 to 0.72 for maize (see Figure 1). The spatial distribution of simulated yields remains consistent across years and does not exhibit systematic regional biases with uncertainty due to different parameter sets remaining small (<0.1 t/ha on average, see Supplementary Material 14).

The calibration procedure substantially improved model performance relative to the default parameterisation, with both steps contributing similarly to the improvement of simulated yields. Detailed calibration statistics and parameter evaluation results are provided in Supplementary Section S5.

4.2 Attribution of yield losses to heat and drought stress

The counterfactual scenarios show that yield declines in Germany in the period 2017 – 2022 were predominantly caused by drought stress. Across all analysed years, LandscapeDNDC shows only minimal yield reduction due to heat stress, and no reduction due to anthesis heat stress.

4.2.1 Heat stress contribution

Heat stress contributed only marginally to simulated yield variability in Germany during the study period. Across all simulated years, reductions in photosynthetic activity due to high-temperature stress were limited and did not translate into substantial yield losses.

For wheat, minor effects of heat stress were detected in the years 2019 and 2022 (Figure 2), however associated yield changes were negligible, 0.01 ± 0.08 t/ha on average, comparable to the difference between parameter sets. No measurable heat-induced yield reduction was simulated for maize.

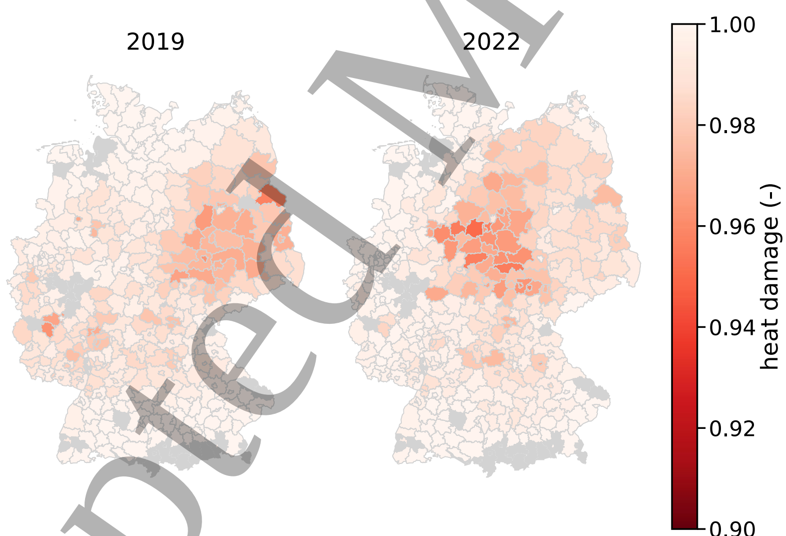


Figure 2: Detected heat stress in wheat, scaled between 1 and 0, with the heat damage scaling plant growth. The heat stress factor ranges from 1 (no heat stress) to 0 (complete inhibition of growth due to heat stress). Note that the colorscale begins at 0.9 for better visibility.

Similarly, anthesis heat stress did not contribute to yield losses for either crop during 2017–2022. This indicates that temperature extremes during flowering were insufficient to induce meaningful reproductive damage under the climatic conditions of the study period. Overall, these results suggest that heat stress played a secondary role compared to drought stress in explaining observed yield reductions in Germany during recent extreme years.

4.2.2 Drought stress contribution

Process attribution shows that drought was the principal driver of yield losses in recent years, resulting in losses of up to 50 % in some districts.

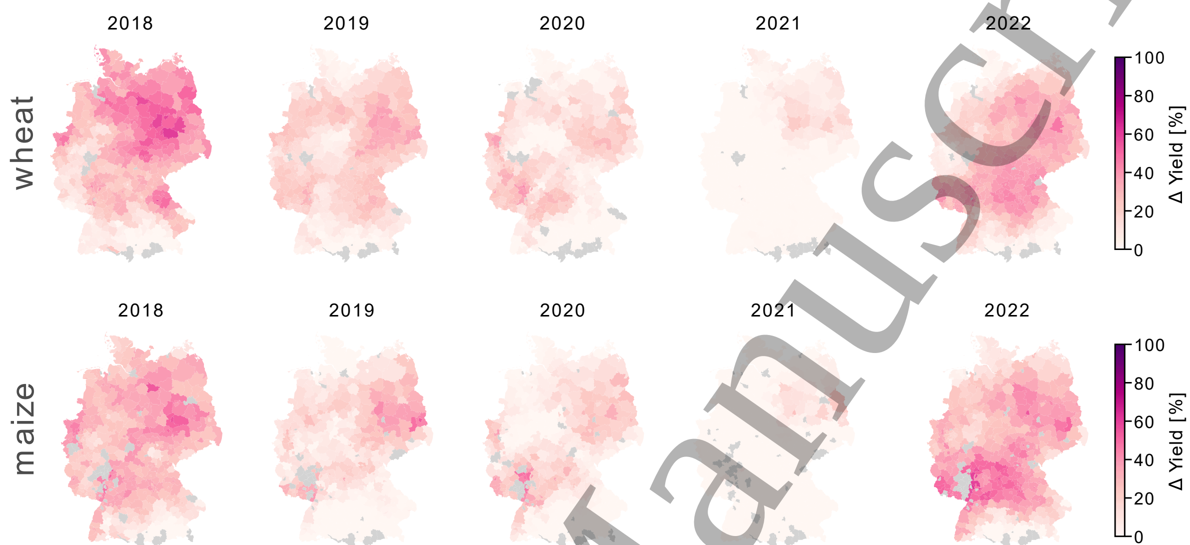


Figure 3: Spatial distribution of simulated drought-induced yield losses (%) for winter wheat (upper row) and silage maize (lower row) from 2018 to 2022. Values represent the proportion of yield loss attributed to drought stress. Grey districts indicate that the respective crop was not present in the simulated crop rotation.

Across Germany, drought caused yields declines of 26 % in 2018 for both maize and wheat. In 2019 the drought conditions were more spatially confined, mainly affecting Brandenburg. The years 2020 and 2021 were close to average conditions in terms of precipitation, with low yield reduction throughout the country. In 2022, the losses attributable to drought were comparable to those in 2018, with an average of 29 % yield loss for maize and 24 % in wheat.

Drought impacts also exhibited strong spatial variability. The largest losses occurred in Saxony-Anhalt, Brandenburg, and parts of the Rhine Valley, where simulated yield reductions exceeded 50%, with local maxima above 70% for winter wheat. In southern Germany yield penalties were much smaller, with an obvious gradient towards the Alps, where losses were minimal, ranging between 0-20 %, and some districts experienced no drought-related yield reductions at all.

Overall, these results demonstrate that drought stress was the primary factor explaining interannual yield variability in Germany during recent extreme years, and the main driver of large-scale yield reductions under climatic extremes.

4.3 Mitigation of drought-induced yield losses with irrigation

Crop yield losses in the period 2017–2022 were almost eliminated by applying irrigation whenever the plant-available water fell below a threshold value. Crop yields simulated under these "irrigation" conditions were very similar to the counterfactual scenario in which drought stress was disabled, with differences across Germany of only 0.1 ± 0.05 t/ha. This indicates that the majority of simulated drought losses resulted directly from water limitation and could theoretically have been avoided through sufficient irrigation.

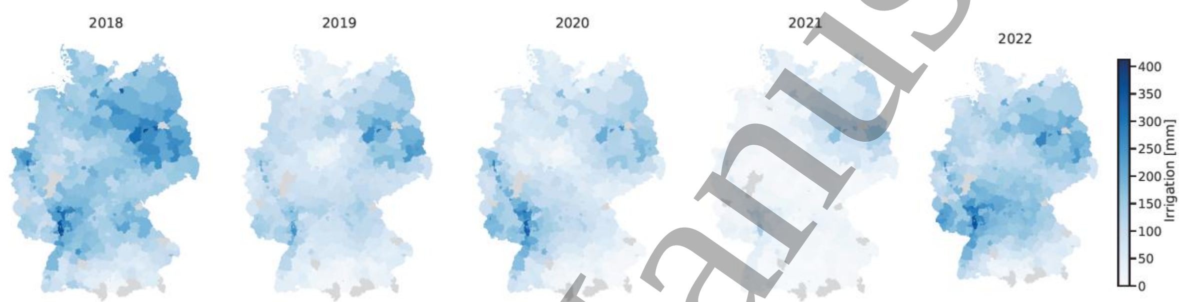
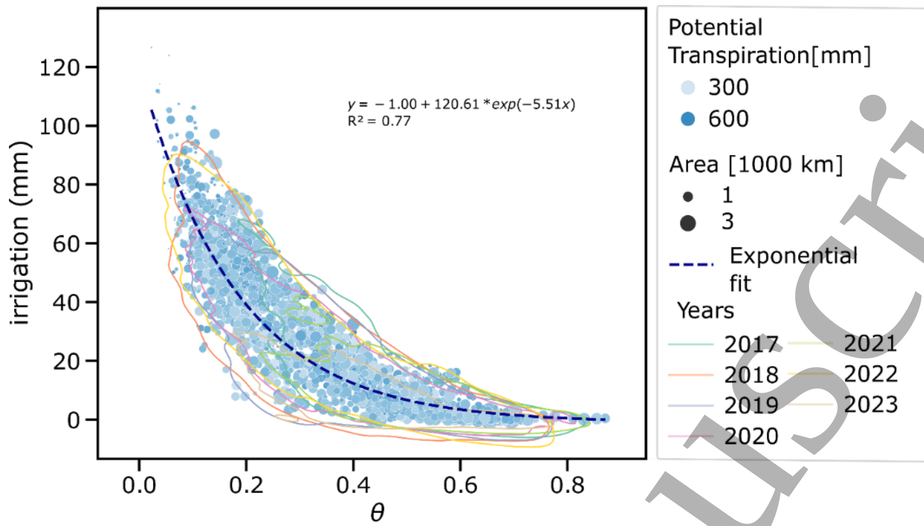


Figure 4: Simulated irrigation requirements (mm yr⁻¹) necessary to mitigate drought-induced yield losses across Germany between 2018 and 2022. Values represent average irrigation applied per field. Grey districts indicate that neither winter wheat nor silage maize was present in the simulated crop rotation.

Figure 4 shows the spatial heterogeneity in irrigation requirements throughout the different years. In 2018, irrigation requirements were the highest, averaging 156 ± 60 mm of water needed to offset the precipitation deficit and maintain adequate plant-available soil moisture. In 2018 and 2022, 95 % of districts required at least some irrigation, with the only exceptions being districts located in the pre-alpine region. The highest irrigation water demand occurred in Brandenburg, Saxony-Anhalt, and the lower Rhine valley, where some districts required over 400 mm of irrigation water per year to ensure sufficient plant water supply. The lowest water requirements were found for the wetter years 2017 and 2021, with an average requirement of 46 ± 7 mm of water.

Additional model runs with lower irrigation thresholds indicate that substantial mitigation could have been achieved with reduced water usage. For instance, in 2018, applying roughly half of the water required for full drought mitigation (85 ± 40 mm) would still have prevented 88 ± 6 % of winter wheat yield losses (=1.4 ± 0.9 t/ha), with a 2.9 t/ha reduction in yield losses in the most drought-affected districts.

261 

262 *Figure 5: Relationship between mean monthly plant-available soil water and simulated irrigation requirements. Points*
263 *represent district-level values, coloured by potential transpiration and scaled by district area. The dashed line shows an*
264 *exponential fit ($R^2 = 0.77$).*

265 Simulated irrigation demand was strongly related to soil water availability (Figure 5). Across
266 years, soil types, and regions, irrigation requirements increased non-linearly with declining
267 plant-available soil water. An exponential relationship explained much of the variability
268 ($R^2 = 0.77$), indicating rapidly increasing water requirements under increasingly dry
269 conditions.

270 # 5 Discussion

271 ## 5.1 Model Calibration

272 Our results indicate that German crop yields can be satisfactorily modelled using aggregated
273 data from just 10 districts per crop, covering both low- and high-stress conditions. Unlike
274 prior site-specific calibrations (Houska et al., 2017; Molina-Herrera et al., 2016), we
275 employed aggregated data for calibration, following earlier studies (e.g. Webber et al. 2018),
276 aiming for the best generalised calibration across different cultivars used on varying
277 agricultural ecosystems.

278 Some of the chosen parameters are closely coupled, meaning that they can compensate for
279 each other. This concept is known as equifinality (Beven and Freer, 2001; Wallach et al.,
280 2021) and indicates that it is possible to accept multiple parameter sets to produce the same
281 output. We selected parameter sets that showed a mid-range for both parameters, to make

sure one process is not penalized by overestimation of the other one. The spread in yield resulting from using different parameter sets is shown in Supplementary Material 14.

The calibration procedure resulted in multiple parameter sets with similar performance, reflecting structural and parametric compensation effects within the model system. Rather than relying on a single optimal parameter set, we therefore retained an ensemble of best-performing solutions to capture plausible parameter space while maintaining consistent model performance across calibration targets (see Supplementary Material 7 – 10).

Our results suggest that a heat stress onset temperature (PSNTMAX) for maize of below 35 °C does not produce a good fit to yield data. This is consistent with impacts on photosynthesis, which suggest that heat stress in maize only becomes significant beyond 38 °C (Cairns et al., 2013; Sánchez et al., 2014). In wheat we find heat stress threshold temperature clustering above 33 °C, consistent with measurements showing tolerance to ambient temperatures up to 40 °C and maximum grain filling temperatures of up to 35 °C (Akter and Islam, 2017).

For anthesis heat stress (TMINCRIT), wheat values range from approximately 31.9 to 34.8 °C. While these thresholds are considerably higher than the 25 °C used in previous modelling studies (Deryng et al., 2014; Martin et al., 2025), they are consistent with measured maximum tolerable values of ~ 32 °C derived from lab studies (Akter and Islam, 2017; Farooq et al., 2011), particularly when considering differences between canopy temperatures used in the model and detailed temperatures reported in experimental studies.

Maize shows a wider range between approximately 23.6 and 49.9 °C. These values fall within the range of reported physiological studies (~ 30 - 32 °C; Cicchino et al., 2010a, 2010b; Rattalino Edreira and Otegui, 2012; Lobell et al., 2013; Rötter et al., 2018; Jagadish, 2020). The broad range reflects limited sensitivity of simulated yields under the climatic conditions of the study period rather than inconsistency with physiological understanding. Importantly, across all parameter sets, anthesis heat stress does not occur with sufficient frequency or intensity to influence simulated yields during the study period.

Overall, the weak constraint on both heat stress parameters implies that parameter uncertainty in the heat response does not propagate into uncertainty in simulated yield losses, which are instead dominated by drought stress. Nevertheless, these processes are retained to ensure transferability to warmer climates and future scenarios where heat stress may become more relevant.

5.2 Model performance across Germany

The calibrated version of LandscapeDNDC reproduces both the magnitude and interannual variability of German crop yields, despite the high spatial heterogeneity of 403 districts simulated. However, wheat yields in 2018 were slightly underestimated, whereas maize yields remain well reproduced. It is possible that this discrepancy stems from not including drought adaptations like irrigation or cultivar variation, suggesting localized management might have secured harvests in some districts. Nevertheless, the model captures the broad spatial and temporal patterns of yield variability associated with recent drought events. Despite remaining limitations, model performance remains comparable to (e.g. Becker et al. 2025) or better (e.g. Peichl et al., 2019; Rezaei et al., 2015) than previous studies conducted for Germany. This provides confidence that the model captures the dominant large-scale controls on crop yield variability and is suitable for process-based attribution analyses.

5.3 Drivers of yield variability during extreme years

The model results suggest that drought is the dominant driver of crop yield declines in Germany in recent years. This is in line with the findings of Webber et al. (2018) using a similar approach on the European level and Webber et al. (2020), combining process-based modelling and a machine learning method.

Heat stress had a minimal impact in our simulations because temperatures rarely exceeded the critical thresholds identified during calibration, which align with literature values from in-situ measurements (e.g. Akter and Islam, 2017; Farooq et al., 2011; Wang et al., 2019). However, we observed a discrepancy with threshold values derived from large-scale data analysis (e.g. Becker et al., 2025; Bogenreuther et al., 2025; Lüttger and Feike, 2018), which determined values 5 – 10 °C lower than both our calibration thresholds and those determined via plant measurements. This discrepancy has been discussed in Lesk et al. (2022) and likely stems from simplified definitions of heat, drought and compound events often employed in statistical studies. As a result, part of the yield response attributed to temperature may reflect drought processes. Unlike data-driven approaches or simpler crop models lacking explicit soil dynamics, LandscapeDNDC captures this interaction through its detailed representation of the pedosphere. Due to the only minor role of heat stress in our analysis, interactive effects also only played a very minor role in the variation of yield, with parameter uncertainty being higher than the role of combined heat and drought stress.

Drought patterns revealed in Figure 3 largely coincide with regions identified by the German drought monitor for soil water deficit in the top 25 cm in 2018 (Mühr et al., 2018), 2019 and 2020 (Boeing et al., 2022), with the most affected regions located in NE Germany. The analysis of stress patterns in vegetation by Gessner et al. (2023) shows a similar regional pattern and low stress-indices in spring, which aligns with our finding that anthesis heat stress had limited impact on yields. Estimated drought-induced yield losses also correspond well with the deficits reported by the German government (BMWE, 2022).

The consistency between simulated drought impacts, independent drought indicators, and reported yield losses provides additional confidence that drought, rather than heat stress, was the dominant driver of crop production losses during the study period.

5.4 Irrigation as a mitigation strategy for drought-induced yield losses

Irrigated simulations demonstrate that a large fraction of drought-induced yield losses could, in principle, be avoided through supplemental irrigation. Across the analysed years, simulated irrigated yields approached those of the counterfactual no-drought scenario, indicating that water limitation was the dominant mechanism responsible for yield reductions.

We identified a universal exponential relationship between monthly plant-available soil water (θ) and irrigation requirement (Figure 5), independent of location or precipitation regime. This universal relationship generalises the district-specific curves of McNamara et al. (2024) by using θ as opposed to the standardised precipitation-evapotranspiration index (SPEI-6), θ offering a more holistic relationship than SPEI. This relationship shows that under increasing climatic extremes (Perkins-Kirkpatrick and Lewis, 2020; Heino et al., 2023), both plant water deficits and irrigation demand are expected to rise exponentially.

A key advantage of LandscapeDNDC is its coupling of hourly water-cycle dynamics with detailed plant development, offering more mechanistic realism than hydrological models relying on simplified plant uptake assumptions (McNamara et al. 2024; Bernhardt et al., 2022). Nevertheless, our approach generally confirms the findings of McNamara et al. (2024) for absolute requirements, with good spatial agreement of regions with the highest irrigation requirements (e.g. Rhineland-Palatinate and Brandenburg). At the national level the difference in water demand is only about 5 %, with LandscapeDNDC estimating slightly lower irrigation requirements.

5.5 Limitations

A key limitation is the absence of an explicit energy balance to dynamically couple canopy temperature with evapotranspiration; instead, heat and drought are applied as separate, multiplicative stress factors. While this approach captures the primary agronomic interaction where heat stress manifests under water-limited conditions, it simplifies the physical feedback (e.g., canopy cooling) that a fully coupled energy balance would resolve.

Other factors not explicitly modelled in this study like frost, waterlogging, or pests can cause local losses, but those were not primary drivers of widespread failures in this period (Webber et al., 2018, 2020). Although disease spread triggered by drought was not explicitly modelled, attributing such indirect effects to drought remains valid. We conclude that LandscapeDNDC captures the dominant large-scale controls on crop yield variability and is suitable for process-based attribution analyses.

The estimated irrigation requirement (7.4 billion m³ for Germany) represents the water demand associated with an idealised strategy to fully mitigate drought-induced crop losses, without considering water availability, infrastructure costs, or sustainability constraints. However, when deciding whether to utilise existing irrigation systems or invest in new infrastructure, it is essential to take these additional factors into account. Intensive irrigation may lower groundwater tables, increasing soil susceptibility to drying, a dynamic already observed in Brandenburg (Francke and Heistermann, 2025). Future planning must balance these ecological limits with the need to increase agricultural resilience.

6 Conclusion

In recent years, extreme droughts have significantly reduced crop yields in Germany. Calibrating against recent data demonstrates that LandscapeDNDC robustly captures the processes governing yield variability, making it well-equipped for attribution of yield losses. The biogeochemical model is now able to accurately simulate yield declines and attribute them across multiple drivers.

Our calibrated LandscapeDNDC simulations indicate that the yield losses in the years from 2018 to 2022 were driven primarily by drought stress, with negligible impacts from heat stress, particularly anthesis heat stress, across all analysed years. Because drought was identified as the main driver of these losses, we were able to show that they could have been theoretically mitigated through the use of irrigation. The identified exponential relationship between plant-available soil water and irrigation requirements provides a crucial foundation for mitigating future extremes.

This platform enables studies on how increasing frequency and severity of weather extremes will affect future yields and biogeochemical cycling (carbon, nitrogen, water) in German croplands. One way to do this would be to drive the model with projections from the Coupled Model Intercomparison Project 6 (CMIP6, e.g. Schmidt and Felsche 2024; Bathiany et al. 2023; Müller et al. 2021). However, it has been shown that extreme events, such as the 2018 - 2020 heat-drought, are not well represented in the CMIP6 ensemble (Hirsch et al., 2021; Kornhuber et al., 2024). An alternative approach to illustrating the dangers of future extreme events on European agriculture is to study storylines, which, for example, reproduce the large-scale climatic conditions of the 2018 – 2022 droughts in a warmer world (Sánchez-Benítez et al., 2022). We have previously demonstrated the potential of this storyline approach for understanding the impact of anthesis heat stress under climate change (Martin et al., 2025).

Beyond yield analysis, LandscapeDNDC can address drought-induced feedbacks on soil carbon and nitrogen fluxes, including nitrate leaching and greenhouse gas emissions (Kraus et al. 2016; Sifounakis et al. 2024; Rahimi et al. 2024; Grados et al. 2024; Smerald et al, in prep.). Accurate crop yield simulations and associated nitrogen uptake are essential for refining inventories of environmental pollutants and predicting their response to climate change and new management practices.

7 Acknowledgements

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8 Data and Code availability

Availability of input data is listed in Supplementary Section S4. Code for LandscapeDNDC can be accessed under https://ldndc.imk-ifu.kit.edu/. Scripts for generating the inputs for LandscapeDNDC can be found at https://gitlab.imk-ifu.kit.edu/smerald/germany_simulator. Results for yields, drought and irrigation outputs can be accessed at Radar4KIT: https://doi.org/10.35097/gcxbhp7e5xn4eaey. Scripts for postprocessing the LandscapeDNDC outputs and generating plots can be found at https://gitlab.imk-ifu.kit.edu/martin-l/gs_analysis.

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