nature food

Brief Communication

https://doi.org/10.1038/s43016-025-01226-8

Energy shortages undermine agricultural drought resistance in the Democratic People's Republic of Korea

Received: 29 November 2023

Accepted: 6 August 2025

Published online: 15 September 2025

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Agricultural systems in low-income food-deficit countries face considerable risks from climate extremes and geopolitical tensions. Here, using remote sensing and meteorological observations, we show that the Democratic People's Republic of Korea exhibits lower agricultural drought resistance than the Republic of Korea under meteorological droughts of similar severity. Energy shortages, exacerbated by trade sanctions, have limited the Democratic People's Republic of Korea's irrigation capacity, further impairing its drought resistance and food security.

Feeding a growing population under increasing frequency and severity of extreme weather events (EWEs) poses a critical challenge, particularly for low-income food-deficit countries (LIFDCs), which are heavily reliant on international aid to ensure food security[1,2]. In addition, these countries are often plagued by external pressures such as geopolitical conflicts and political instability, which further strain food security[3]. Achieving food security goals in LIFDCs depends not only on food production capacity but also on international assistance[4,5]. Yet, even though stable international relations and reliable energy supplies are essential for sustaining food security[6], few studies have focused on the impact of external pressures, such as sanctions, on food security[7]. Considering the increasing EWEs and geopolitical instability, this knowledge gap may hinder progress towards global food security, especially in LIFDCs[3,8].

A comparison between the Democratic People's Republic of Korea (DPRK) and the Republic of Korea (ROK) is a valuable case for addressing this knowledge gap. Despite sharing the Korean Peninsula's similar climate and geography (Supplementary Fig. 1), the DPRK endures persistent food crises[9], with approximately 41% of its population experiencing undernourishment (Supplementary Fig. 2). This situation is projected to worsen due to escalating EWEs[2]. By contrast, the ROK experiences comparatively minor crop damage from climate disasters[10]. In addition to the effects of EWEs, factors such as agricultural infrastructure, crop varieties and fertilizer use[11,12] also contribute to the yield disparity between the two countries. The DPRK has also been subject to successive external pressures due to the nuclear weapons program, including restrictions on crude oil imports[13], and financial limitations on its Foreign Trade Bank[14]. While these constraints may have impacted the country's agricultural sector, the impacts of the external pressures on the two countries' stark disparity in terms of agricultural resistance remain elusive.

This study uses remote sensing and meteorological observations to evaluate the impact of the 2015 drought on rice and to investigate its underlying drivers. Rice was chosen for this exercise because it accounts for over 60% of the DPRK's food production and is therefore a critical staple that profoundly shapes the nation's cropping patterns and agricultural output[15]. The adverse effects of EWEs on rice are intensifying amid climate change[16]; drought, characterized by a

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https://doi.org/10.1038/s43016-025-01226-8

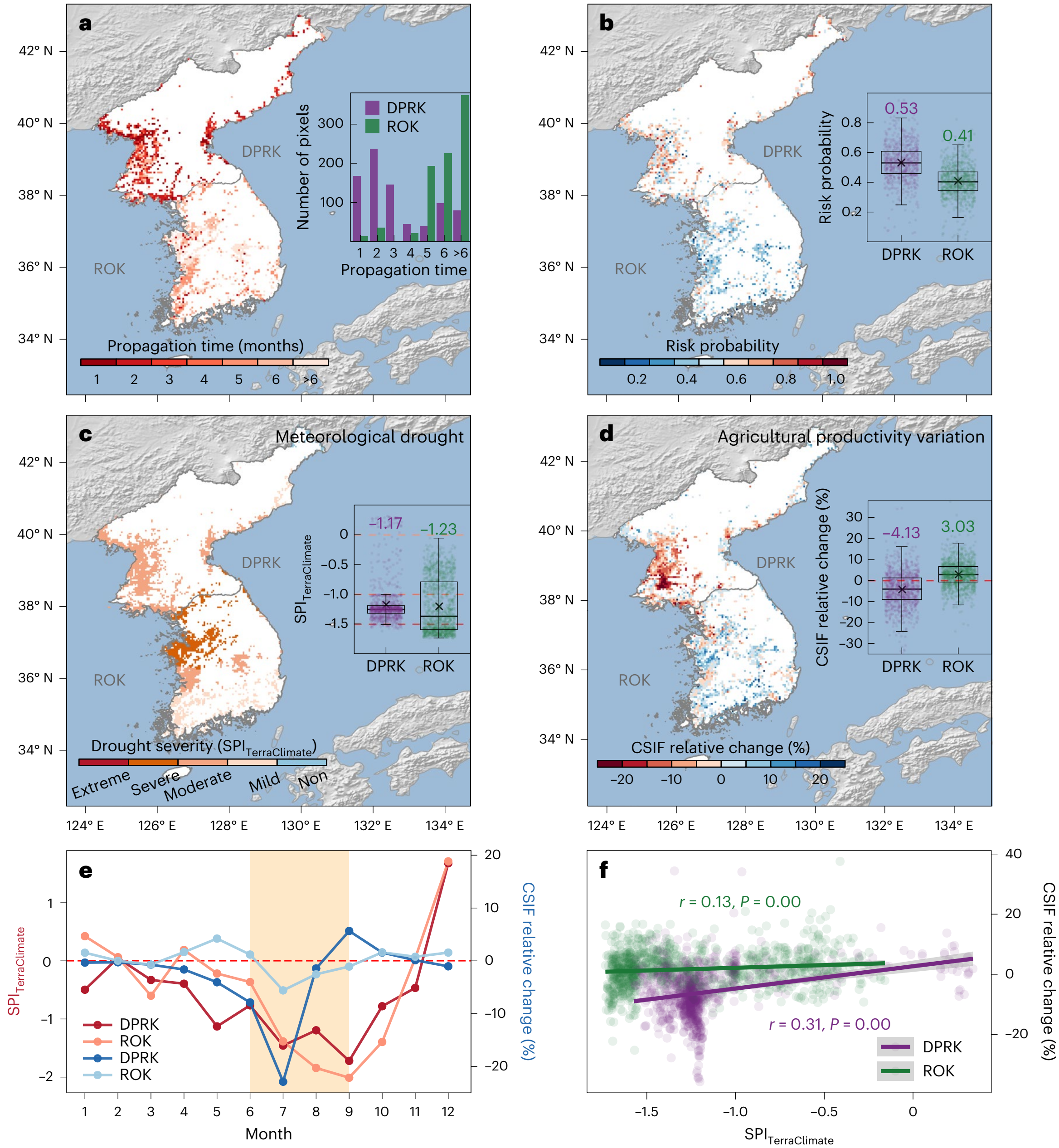

Fig. 1 | Long-chain drought propagation and the contrasting responses of rice growth to the 2015 drought in the DPRK and ROK. a,b, Spatial variation of drought propagation time and risk probability across the Korean Peninsula. The insets correspond to the propagation time (**a**) and risk probability (**b**) of the DPRK and ROK, and the numbers in **b** indicate the mean value of risk probability. **c**,**d**, Spatial pattern of meteorological drought and agricultural productivity variation during the 2015 rice-growing period. The boxes correspond to $SPI_{TerraClimate}$ (**c**) and CSIF relative change (**d**) of the DPRK and ROK, and the numbers indicate the mean value. Box plots in **b**–**d** represent the distribution of pixel values for the DPRK and ROK. Sample sizes (n) are as follows: **b**, $n_{DPRK} = 810$, $n_{ROK} = 864$; **c**, $n_{DPRK} = 1{,}225$, $n_{ROK} = 1{,}346$; **d**, $n_{DPRK} = 1{,}087$, $n_{ROK} = 1{,}270$. The centre line indicates the median, the cross denotes the mean, the box spans the interquartile range, and the whiskers extend to the most extreme data points within 1.5 × interquartile range. Basemaps in **a**–**d** are from Natural Earth (https://www.naturalearthdata.com/). Non, non-drought. **e**, Seasonal dynamics of SPI and CSIF relative change in the DPRK and ROK. The orange shading denotes the primary rice growing season in both the DPRK and ROK. **f**, Correlation between SPI and CSIF relative change during the growing season for the DPRK and ROK. Pearson correlation analysis was performed separately for each country using two-sided tests. The grey shading around the regression lines represents the 95% confidence intervals of the fitted linear models.

precipitation deficit that propagates through the hydrological cycle, is among the most destructive and costly EWEs[17]. We address two questions: (1) what are the differences in crop resistance to drought between the DPRK and ROK? (2) what is the impact of external pressures on drought resistance in the DPRK?

We depicted meteorological droughts using the Standardized Precipitation Index (SPI) derived from three datasets: TerraClimate ($SPI_{TerraClimate}$), Climate Hazards Group InfraRed Precipitation with Station (SPI_{CHIRPS}) and Integrated Multi-satellitE Retrievals for GPM (SPI_{IMERG}). The results show that meteorological drought in the DPRK propagates more rapidly and with a higher risk probability than in the ROK (Fig. 1a,b and Supplementary Figs. 3–10). The drought propagation time in the DPRK is generally less than 3 months, whereas it exceeds 5 months in the ROK (Fig. 1a). In addition, the DPRK's drought risk probability (0.53) surpasses that of the ROK (0.41) (Fig. 1b). In 2015, during the rice-growing season, the ROK experienced more

 https://doi.org/10.1038/s43016-025-01226-8

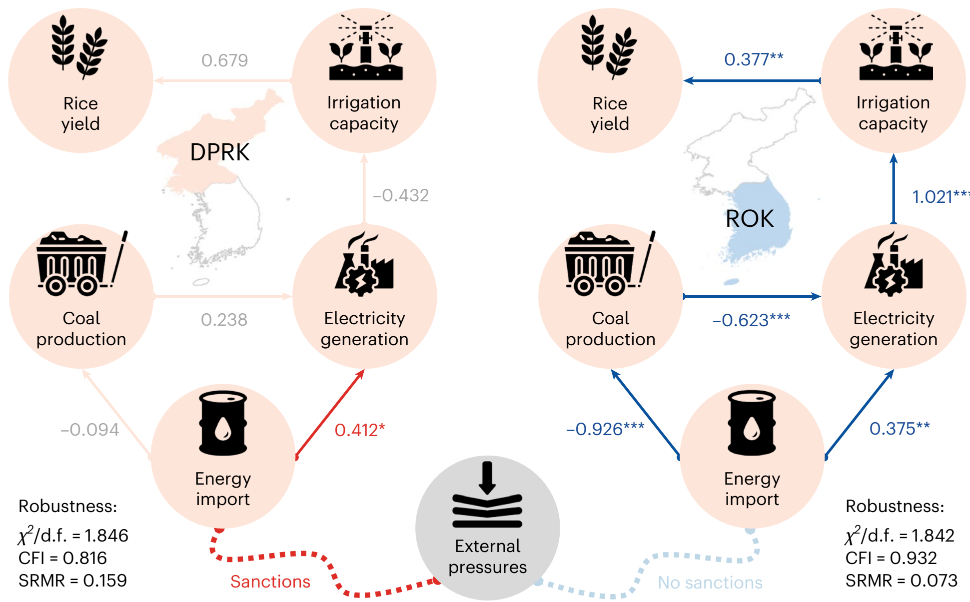

Fig. 2 | Effects of external pressures on the rice yield in the DPRK and ROK. Dark-red and dark-blue arrows represent significant pathways for the DPRK and ROK, respectively, while light-red arrows indicate non-significant pathways. Standardized path coefficients are shown adjacent to arrows, with grey indicating non-significant paths. Path significance was assessed using two-sided tests based on maximum likelihood estimation in structural equation modelling. $^{***}P < 0.01$; $^{**}0.01 \leq P < 0.05$; $^{*}0.05 \leq P < 0.01$. Exact P values for all paths are provided in Supplementary Table 4. Basemaps of the DPRK and ROK are from Natural Earth (https://www.naturalearthdata.com/). Credit: icons, Flaticon.com.

severe meteorological drought than the DPRK, with 39.9% of its area in severe drought, 24.8% in moderate drought and 35.3% in mild drought (Fig. 1c and Supplementary Fig. 11). Conversely, in the DPRK, only 3.3% of rice-growing areas experienced severe meteorological drought, with 86.9% in moderate and 5.9% in mild drought (Fig. 1c). These results, supported by SPI_{CHIRPS} and SPI_{IMERG} (Supplementary Figs. 12 and 13), reveal a consistent pattern of more severe meteorological drought in the ROK compared with the DPRK.

Despite experiencing more severe meteorological drought than the DPRK, the ROK sustained less agricultural productivity loss than the DPRK (Fig. 1d). To assess agricultural productivity variations, we utilized contiguous solar-induced chlorophyll fluorescence (CSIF)[18], enhanced vegetation index (EVI) and near-infrared reflectance (NIR_V) as proxies. In the DPRK, CSIF relative change exhibited a notable decrease (4.1%) compared to the baseline (Fig. 1d). Instead of decreasing, CSIF relative change in the ROK increased by 3.0% (Fig. 1d), indicating minimal impact on rice growth, confined to isolated areas (Fig. 1d). Throughout the rice-growing period, the DPRK's CSIF relative change declined steadily, peaking at a 22.9% drop in July. This decline corresponds to a 67.5 gC m^{-2} reduction in gross primary productivity—2.2 times the reduction observed in the ROK (Fig. 1e and Supplementary Fig. 14). Conversely, the ROK's CSIF remained stable, with only a slight decrease in July and August (5.6%), indicating a more stable rice growth (Fig. 1e). The relative change in EVI and NIR_V also confirmed a more pronounced productivity reduction in the DPRK than in the ROK (Supplementary Figs. 15–17). The higher correlation between $SPI_{TerraClimate}$ and CSIF relative change during the rice-growing season in the DPRK further suggests its lower drought resistance (Fig. 1f). The 2015 drought, primarily affecting June to September, overlapped with the crucial rice-growing season in both countries (Fig. 1e and Supplementary Fig. 11), which may have partially affected rice productivity. The DPRK experienced a drastic 16.4% decline in rice yields in 2015 compared with the previous year, while the ROK recorded a surprising 4.4% yield increase (Extended Data Fig. 1a).

To minimize the effects of spatial heterogeneity, we analysed the drought impacts on rice growth, focusing on two regions near the country boundaries (selected for their more consistent climatic and geographic contexts). The results consistently demonstrated that, despite similar meteorological droughts, the region in the DPRK experienced a markedly greater loss of agricultural productivity than the ROK (Supplementary Fig. 18), aligning with national-level findings.

We further conducted a structural equation model (SEM) to explore potential pathways influencing the DPRK's agricultural drought resistance (Fig. 2). Although the DPRK has a higher proportion of croplands equipped for irrigation (57%) and a larger total dam capacity (21.2 km^3) than the ROK (46% and 18.8 km^3) since 1991 (even though not all the dams may be used for agricultural irrigation) (Extended Data Fig. 1b,c), its drought resistance remains weaker (Fig. 1). This discrepancy may stem from the DPRK's lower agricultural irrigation water use efficiency and water consumption coefficient, both of which have declined further following sanctions (Extended Data Fig. 1d,e and Supplementary Fig. 19). Energy shortages probably exacerbate this inefficiency, as insufficient domestic coal production, compounded by restricted energy imports under external pressures, has limited electricity generation for irrigation (Fig. 2 and Extended Data Fig. 1f–i). Unlike the ROK, which compensates by energy imports, the DPRK's reliance on imports has been severely impacted by external pressures, further restricting its irrigation capacity and rice yield (Fig. 2 and Extended Data Fig. 1). The DPRK developed an industrial agriculture heavily reliant on imports from the 1950s until the 1990s, when the collapse of the socialist economic bloc drastically reduced such external support[11,19]. While efforts to restore productivity have focused on technologies such as gravity-fed irrigation[11], these gains are once again threatened by international sanctions and associated constraints[20].

The impact of external pressures on agricultural drought resistance in the DPRK primarily manifests through limitations in irrigation capacity, which depends on both diesel-powered and electricity-based irrigation systems[11]. First, the shortage of diesel fuel for irrigation pumps—partly attributed to sanctions—has restricted irrigation capacity and agricultural productivity. Secondly, the country's electricity generation is impeded not only by restrictions on crude oil and coal imports but also by long-term infrastructure degradation and limited access to power generation equipment and technology, further restricting irrigation capacity (Extended Data Fig. 1h,i and Supplementary Fig. 20). Consequently, the DPRK's electricity generation has declined by approximately 30%, further diminishing irrigation capacity and indirectly compromising agricultural drought resistance[11] (Extended Data Fig. 1f and Supplementary Fig. 21). Furthermore, the shortage of diesel fuel for tractors and other agricultural machinery disrupts harvesting efficiency, completeness and post-harvest food storage, thereby intensifying food security challenges.

Moreover, external sanctions have influenced the DPRK's access to food aid and imports since 2006, further aggravating food insecurity (Supplementary Figs. 22 and 23). The DPRK has consistently exhibited higher malnutrition rates than the ROK, with undernourishment rates frequently nearing 50% (Supplementary Fig. 2), a situation potentially aggravated by drought-related yield declines. In addition to external pressures, other factors also influence agricultural resistance, such as fertilizer use and crop varieties[21,22]. For instance, a marked decline in nitrogen fertilizer production and usage occurred in the DPRK around 1993–1994, with levels remaining persistently low since, probably undermining food production (Supplementary Figs. 24 and 25).

Our study provides spatiotemporally explicit evidence of the disparities in drought resistance between the DPRK and ROK. Despite similar meteorological droughts, the DPRK experienced notably greater agricultural productivity losses (Fig. 1). Energy shortages—partly exacerbated by sanctions—have constrained irrigation capacity, further weakening the DPRK's drought mitigation capacity and food security (Fig. 2 and Extended Data Fig. 1). These findings advance the current understanding of the food–energy–water nexus by demonstrating how external pressures, such as sanctions, affect the extended causal chain 'energy import decrease → energy shortages → reduced irrigation capacity (weakened agricultural drought resistance) → crop yield loss'. This framework provides insight into the contrasting agricultural drought resistance between the DPRK and ROK.

External pressures—including formal sanctions from the United Nations Security Council (which began in 2006) and earlier unilateral measures by the international community—have exacerbated the DPRK's vulnerability to droughts by restricting energy supplies and limiting food aid. Still, it is crucial to recognize that sanctions are only one of multiple contributing factors to the weakening of agricultural drought resistance. The DPRK's agricultural challenges stem from a complex interplay of factors, including not only external sanctions but also domestic economic and political choices, long-term grid degradation and limited access to modern technology and resources[11].

In conclusion, the DPRK's experience highlights the urgent need for LIFDCs to strengthen agricultural drought resistance and maintain stable international relations. These countries face heightened vulnerability due to their limited capacity to adapt to climate change and geopolitical instability[3,8,23], further exacerbated by the increasing frequency and intensity of EWEs[24]. Our analysis illustrates the broad implications for countries and regions grappling with comparable sustainability challenges; the DPRK's situation serves as a cautionary tale for LIFDCs, demonstrating the crucial need for modernized agricultural systems and stable international relations.

Methods

This study utilized multisource remote sensing data, meteorological data and statistics to investigate the differential responses of rice growth to drought in the DPRK and ROK, as well as to explore the underlying factors (Supplementary Table 1). We quantitatively characterized the long-chain drought propagation process using a dynamic threshold framework[25]. This framework includes the calculation of drought propagation time based on Pearson correlation coefficients and the computation of drought risk trigger probabilities using copula functions (Supplementary Text 1).

We used satellite and meteorological data to characterize drought patterns in the DPRK and ROK. Meteorological drought is commonly defined by the precipitation deficit and the duration of the dry period[26]. SPI is widely used to monitor meteorological drought, with the 3-month SPI showing better performance[27]. We calculated SPI using precipitation data from three datasets with different spatial resolutions, including TerraClimate ($SPI_{TerraClimate}$) (1/24°, monthly)[28], SPI_{CHIRPS} (0.05°, monthly)[29] and SPI_{IMERG} (0.1°, monthly)[30]. Detailed formulas are available in ref. 27. A lower SPI value indicates a more severe meteorological drought (Supplementary Table 2).

To represent variations in agricultural productivity, we use the CSIF dataset, which has 0.05° spatial and 4-day temporal resolution with good performance in drought monitoring[18]. The 2015 rice map was obtained from ref. 31, with 500 m resolution, and resampled to match SPI and CSIF. In addition, we used EVI, NIR_V and LSWI derived from the MCD43A4 Collection 6 dataset to assess the severity of agricultural productivity losses, thereby providing supplementary evidence to support the CSIF findings. To quantify drought impact on rice, we calculated the relative change of each index in 2015 relative to a baseline period, which includes the years 2003, 2004, 2006, 2010, 2012 and 2013—years characterized by the absence of drought events (Supplementary Text 2 and Supplementary Fig. 26).

We applied an SEM to quantify the relationships among energy imports, electricity generation, irrigation capacity and rice yield. Drawing on potential causal links suggested in prior studies[11,19,20], our SEM was developed using statistics and satellite data on energy import (crude oil and coal import), coal production, electricity generation, irrigation capacity and rice yield from 1995 to 2020. Given the DPRK's restricted data access, more detailed information is challenging to obtain. External pressures such as sanctions primarily impact energy imports, particularly crude oil and coal. For irrigation capacity, we assessed metrics including water use efficiency, water consumption coefficient and total dam capacity. All variables were standardized using Z scores before SEM to ensure comparability. Model performance was evaluated using chi-square adjusted by degrees of freedom (χ^2/d.f.), robust comparative fit index (CFI) and standardized root mean square residual (SRMR) to evaluate model performance (for more details, see the Supplementary Text 3). We also discussed multiple factors contributing to the DPRK's lower agricultural resistance. Through the comprehensive analysis, we expect to gain a deeper understanding of the factors impeding the enhancement of agricultural resistance in the DPRK.

To ensure the reliability of our analysis, we performed comprehensive validation of all key datasets, including ground-station-based validation for meteorological data, cross-sensor comparisons for vegetation indices, and rigorous documentation of statistical data quality (Supplementary Texts 4–7, Supplementary Figs. 27–32 and Supplementary Table 3).

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The TerraClimate dataset is available at https://www.climatologylab.org/terraclimate.html. The Climate Hazards Group InfraRed Precipitation with Station is available at https://chc.ucsb.edu/data/chirps. The Integrated Multi-satellitE Retrievals for GPM is available at https://disc.gsfc.nasa.gov/datasets/GPM_3IMERGM_07/summary?keywords=GPM_3IMERGM_07. The CSIF dataset used in the analysis is available via figshare at https://doi.org/10.6084/m9.figshare.6387494.v2 (ref. 32). The MCD43A4 Collection 6 dataset is available at https://lpdaac.usgs.gov/products/mcd43a4v006/. The annual maps of rice crops are available from ref. 31. All statistical data used in the study (such as cropland equipped for irrigation, water use efficiency, fertilizer imports and coal imports) can be found via GitHub in the Excel file Data_Statistics.xlsx at https://github.com/QiangHHZ/Sanctions-Drought-Korea/blob/main/

Data/Data_Statistics.xlsx. A detailed description and active links for each statistical variable are provided in Supplementary Table 1. Source data are provided with this paper.

Code availability

All the scripts for the data analyses and visualization are available via GitHub at https://github.com/QiangHHZ/Sanctions-Drought-Korea/tree/main/Codes.

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Acknowledgements

We acknowledge support from the National Natural Science Foundation of China (grant nos. 42271375, J.D.; 42461144212, J.D.), and the Youth Interdisciplinary Team Project of the Chinese Academy of Sciences (grant no. JCTD-2021-04, J.D.). We thank Y. Ryu at Seoul National University, X. He at the National University of Singapore, G. Zhang at the China Agricultural University and N. You at the Chinese Academy of Sciences for their valuable comments in the initial stage of this study and for editing the paper.

Author contributions

J.D., Q.Z. and Q.G. conceptualized and designed the study. Q.Z. collected and processed the data, performed the analysis, constructed the figures and wrote the initial paper. S.G. and S.H. assisted in the analysis of long-chain drought propagation. All authors contributed to writing, reviewing and editing the paper.

Competing interests

The authors declare no competing interests.

Additional information

Extended data Extended data is available for this paper at https://doi.org/10.1038/s43016-025-01226-8.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43016-025-01226-8.

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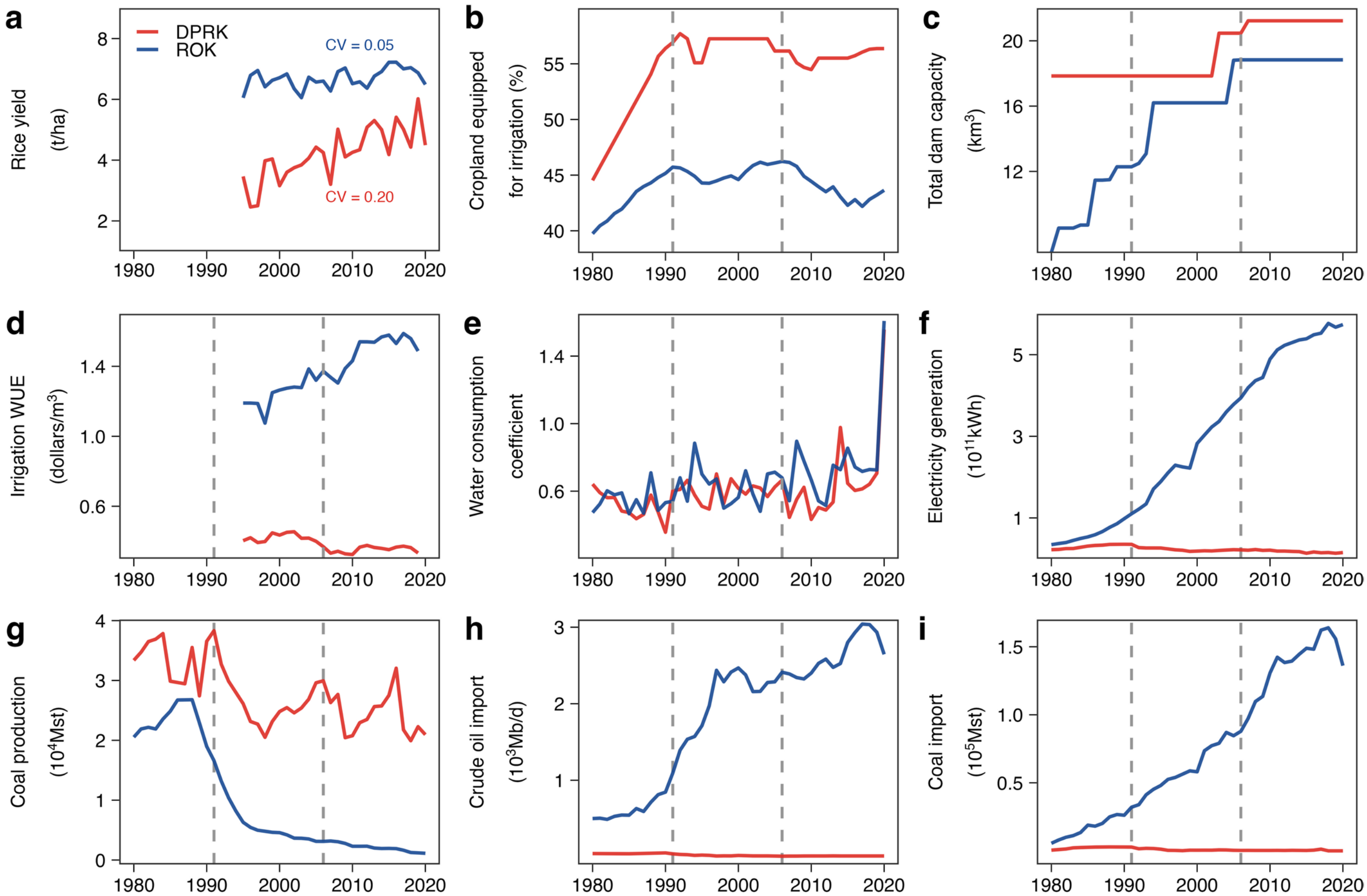
Peer review information *Nature Food* thanks David Von Hippel and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

 https://doi.org/10.1038/s43016-025-01226-8



Extended Data Fig. 1 | Temporal dynamics of key variables influencing rice yield in the DPRK and ROK. **a**, Rice yield in the DPRK and ROK since 1995, with coefficient of variation (CV) values for the both countries. **b**–**e**, Comparisons of irrigation capacity, including cropland equipped for irrigation, total dam capacity, water use efficiency of irrigation agriculture (WUE), and water consumption coefficient. Agricultural irrigation WUE represents the Gross Value Added per unit of water used (expressed in dollars/m^3) of the agricultural irrigation sector. **f**, Changes in electricity generation in the DPRK and ROK since 1980. **g**, Changes in coal production in the DPRK and ROK since 1980. **h**–**i**, Comparisons of energy imports, including crude oil and coal, in the DPRK and ROK since 1980. Gray vertical dashed lines in **b**–**i** correspondingly indicate the dissolution of the Soviet Union (1991) and the onset of sanctions on the DPRK due to its nuclear program (2006).

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Last updated by author(s): Aug 3, 2025

Reporting Summary

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Software and code

Policy information about availability of computer code

Data collection	All data used in this study were collected from freely-available open-source databases. A full list of data sources, including citations and active links, is provided in the section of Data availability and Supplementary Table 1.
Data analysis	The data analyses were performed using Google Earth Engine, ArcGIS 10.7, R v4.2.1, and Matlab 2018a. Details were reported in the section of Methods. All code used to conduct the analyses, and sufficient to reproduce results could be available at https://github.com/QiangHHZ/Sanctions-Drought-Korea.

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- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

The TerraClimate dataset can be available from https://www.climatologylab.org/terraclimate.html. The Climate Hazards Group InfraRed Precipitation with Station is available at https://chc.ucsb.edu/data/chirps. The Integrated Multi-satellitE Retrievals for GPM can be found at https://disc.gsfc.nasa.gov/datasets/GPM_3IMERGM_07/summary?keywords=GPM_3IMERGM_07. The CSIF dataset used in the analysis can be accessed at https://figshare.com/articles/CSIF/6387494. The MCD43A4 collection 6 dataset is available at https://lpdaac.usgs.gov/products/mcd43a4v006/. The annual maps of rice crops are available from Zhang et al33. The icons in Fig. 2 were downloaded from the Flaticon (https://www.flaticon.com/). All statistical data used in the study (such as cropland equipped for irrigation, water use efficiency, fertilizer imports, and coal imports) can be found in the Excel file (Data_Statistics.xlsx) at https://github.com/QiangHHZ/Sanctions-Drought-Korea/blob/main/Data/Data_Statistics.xlsx. A detailed description and active links for each statistical variable are provided in Supplementary Table 1.

Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	Our study is not relevant with human characteristics such as sex and gender.
Reporting on race, ethnicity, or other socially relevant groupings	Our study is not relevant race, ethnicity, or other socially relevant groupings.
Population characteristics	Our study is not relevant with population characteristics.
Recruitment	We do not have human participants in this work.
Ethics oversight	Our study is not relevant with this issue

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This study utilized multi-source remote sensing data, meteorological data, and statistics to investigate the differential responses of rice growth to drought in Democratic People's Republic of Korea (DPRK) and Republic of Korea (ROK), as well as to explore the underlying factors. We chose DPRK and ROK as the representative proxies of LIFDCs and developed nations, respectively. Drought, as a typical extreme event, was selected for analysis. We first quantitatively characterized the long-chain drought propagation process using a dynamic threshold framework. We then depicted meteorological droughts by the Standardized Precipitation Index (SPI) based on three different datasets, including TerraClimate, CHIRPS, and IMERG. And then we assess agricultural productivity change by utilizing CSIF, EVI, and NIRv. Finally, we used a structural equation model (SEM) to quantify the relationships among sanctions, energy imports, electricity generation, irrigation capacity, and rice yield loss.
Research sample	Our study covers the all rice areas in DPRK and ROK.
Sampling strategy	We selected 2015 as the drought year and 2003, 2004, 2006, 2010, 2012, and 2013 as the baseline years. Only paddy rice areas in DPRK and ROK was considered in the study, excluding other crop types. In the re-sampling process (matching SPI and CSIF), we selected only pixels with rice proportion greater than 50%.
Data collection	All data used in this study were collected from freely-available open-source databases, such as the FAOSTAT and the International Energy Agency. A full list of data sources, including citations and links, is provided in the section of Data availability and Supplementary Table 1.
Timing and spatial scale	This study consider the drought year (2015) and the baseline year (2003, 2004, 2006, 2010, 2012, and 2013) in DPRK and ROK. The SPI was calculated based on three datasets, including TerraClimate (1/24°, monthly), CHIRPS (0.05°, monthly), and IMERG (0.1°, monthly). The CSIF dataset has 0.05° spatial and 4-d temporal resolution. The rice maps used for this study have a 500m resolution, and was resampled to match SPI and CSIF data, respectively.
Data exclusions	When re-sampling the rice layer to match SPI and CSIF, we excluded pixels with less than 50% rice proportion. Data from the rice non-growing season were also excluded when calculating the spatial pattern of drought.
Reproducibility	The code for each experiment and analysis was ran multiple times to verify the reproducibility.
Randomization	Not applicable (no experimental trials with a control and intervention).

Blinding | Not applicable for this study.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Plants

Seed stocks	Not applicable for this study.
Novel plant genotypes	Not applicable for this study.
Authentication	Not applicable for this study.