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Regional differences in the performance of drought mitigation measures in 12 major wheat-growing regions of the world

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ABSTRACT

Drought is considered one of the key barriers influencing wheat production, and various adaptation schemes are practiced globally to mitigate drought impacts. However, it is difficult to precisely assess the performances of drought mitigation measures, especially when multiple measures are implemented simultaneously. Here, a remote sensing-based agricultural drought-affected area change index (ADAC) was applied to assess the performance of drought mitigation schemes, which separates and avoids confusion between performances of drought mitigation and wheat yield improvement. The results revealed the historical performance changes and regional differences under drought mitigation measures in 12 major wheat-growing regions (WGRs) of the world. The drought mitigation efforts have steadily succeeded, with a reduction in the drought-affected area of approximately 14.5 % in the 1980s and 28.5 % in the last decade, relatively 55 % of drought-affected areas are alleviated in the 12 WGRs. However, there are significant regional differences ranging from 28 % to 79 % in the 12 WGRs. The drought mitigation measures implemented in the WGRs of China and India, followed by France and Ukraine, are more effective than other regions, while a few are still declining. By further evaluating the effects of short-term and long-term drought mitigation strategies taken in the WGRs, we found that irrigation is the main drought mitigation measure in dryland, while measures such as conservation tillage are of great value for yield stability for both dry and wet areas. The results of this study improve the understanding of the regional performance of drought mitigation schemes and will help stakeholders to select appropriate measures.

1. Introduction

Wheat is the world's primary field crop, accounting for 30 % of the world's total harvested cereal area and approximately 26 % of total cereal production (FAO, 2019). The water requirement of wheat is relatively low compared to that of other staple crops (Pereira et al., 2021), and wheat has the ability to withstand substantial reductions in water availability over relatively long periods of time (Daryanto et al., 2016), making wheat an important crop in rainfed or dryland areas (Trnka et al., 2019). Globally, wheat is the first rainfed crop and the second irrigated crop after rice in terms of production (Lobell, 2014; Shiferaw et al., 2013).

Drought is considered one of the key barriers influencing wheat production (Lesk et al., 2016; Reynolds et al., 2016; Zampieri et al., 2017). Globally, climate variability accounts for approximately one-third of the observed wheat yield changes (Ray et al., 2015), but the degree of yield variance has also changed over time considering that wheat production has increased due to adaptive measures supported by irrigation, drought-tolerant varieties, conservation programs, and early warning systems. Without the application of climate adaptation or drought mitigation measures, up to 60 % of wheat cultivation will face severe water shortages by the end of the century (Trnka et al., 2019).

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Recent evidence suggests that variations in agricultural prices are linked to the occurrence of large-scale droughts (Schewe et al., 2017). Drought was one of the key drivers of the 2007/2008 world food price spikes (Headey, 2011). It is important to understand the effects of existing measures in adapting to climate variability, particularly extreme weather events such as droughts (Chen et al., 2014).

Without human intervention, natural climate variability controls the amount of water that can be expected at any given location (AghaKouchak et al., 2021). Drought is a climatic event that cannot be prevented, but interventions can help mitigate the negative impacts of droughts (Solh and van Ginkel, 2014). Agricultural drought refers to the decline in soil moisture over a period of time, which leads to crop failure (Mishra and Singh, 2010). However, actual agricultural drought is the result of an interplay between a natural event and human interventions. Agricultural drought impacts are minimized or the actual agricultural drought may not occur if drought mitigation measures are appropriately implemented in time to preserve soil moisture and meet the crop water requirements (Van Loon et al., 2016; Wu et al., 2020), even after meteorological drought occurs from a significant reduction in precipitation (Hayes et al., 2012; Pablos et al., 2017). The agricultural drought impacts could also be exacerbated by overuse and poor management of scarce water resources (Aghakouchak et al., 2015; AghaKouchak et al., 2021).

Various drought mitigation measures have been developed, including irrigation practices (Hornbeck and Keskin, 2014; Troy et al., 2015; Uwizeyimana et al., 2018), the use of drought-tolerant cultivars (Simtowe et al., 2019), crop intensity adjustments (Solh and van Ginkel, 2014), agricultural water conservation methods such as mulching and ridges (Uwizeyimana et al., 2018), fertilization management practices (Xiao and Tao, 2014), and small-farming practices to avoid crop failure during dry weather conditions (Dobler-Morales and Bocco, 2021). Irrigation is broadly implemented in China, India, the USA and Pakistan (Siebert et al., 2015; Xie et al., 2019; Zaveri and Lobell, 2019; Zhang et al., 2019). These measures have minimized the agricultural drought impacts in lowering their extent, intensity, duration and frequency (Wang et al., 2016; Wu et al., 2020) or improving crop yield. Various adaptation schemes that may combine different drought mitigation measures are practiced globally in major WGRs.

Models are used to plan irrigation, support decision making when scheduling irrigation events based on the crop, soil, climate and management objectives (Liu et al., 2022; Pereira et al., 2020) and evaluate the impact of drought mitigation measures (Lobell et al., 2015; Yang et al., 2020). Globally, the attainable irrigated wheat yields are 34 ± 9 % higher than the rainfed yields (Wang et al., 2021). Irrigation increased the total biomass yield in the U.S. High Plains by an average of 51 % over 1960–2007 (Suarez et al., 2019). In India, wheat yields increased by 13 % in the 2000s after irrigation became available (Zaveri and Lobell, 2019). Planting alternative varieties of drought-enduring crops or adopting beneficial field management practices can also help reduce drought-induced yield loss by 10–15 % (Li et al., 2018). Government support that may include releasing early warning information and providing postdisaster, technical and financial services has significantly improved farmers' ability to combat droughts, but such improvements have rarely been quantified (Chen et al., 2014; Wang et al., 2015). However, it is difficult to precisely assess the performance of a drought mitigation measure, especially when multiple measures are implemented simultaneously, while avoiding mixing the drought mitigation performance with crop production improvements, such as water productivity. Therefore, agricultural drought characteristics are used to quantify the performance of drought mitigation measures (Wu et al., 2020).

Evaluating the performance of drought mitigation measures and their spatial and temporal implications is critical for drought mitigation planning. This information can help farmers, government agencies, and other stakeholders to understand the availability and gaps in drought mitigation measures and can support the development and implementation of better adaptation schemes. This, in turn, will guide field-, county- and national-level officials to identify gaps in their drought management strategies, thus improving global food security (Zipper et al., 2016).

The present study analyzes the historical changes in drought characteristics and the performances of drought mitigation measures practiced in 12 representative WGRs across the globe. Such an analysis will increase the understanding of the regional performances of drought mitigation measures and will help stakeholders select adaptation measures.

2. Materials and methods

Twelve representative WGRs with various climate systems across the world (Fig. 1 and Table 1) were selected for this study, accounting for 71 % of the global wheat-growing area, 71 % of global wheat production, and more than 82 % of global wheat exports (FAO, 2019). The most intensive wheat cultivation occurs in the temperate latitudes of both hemispheres. Wheat is most prevalent in northern China, the Great Plains of the United States, the Canadian Prairie provinces, the Indus and the upper Ganges Valleys, along the Kazakhstan and Russian border, in southern Australia, throughout Europe, including Turkey, and in southern South America (Leff et al., 2004).

The crop mask data used in this study were acquired from the Land Use and Global Environment (LUGE) laboratory at the University of British Columbia (http://www.earthstat.org/harvested-area-yield-4-crops-1995-2005/). We extracted the wheat area, and pixel values higher than 10 % were regarded as the wheat-growing area (Ray et al., 2012). The crop mask data were combined with the cropland cover data to generate a more accurate crop distribution data layer. The cropland cover data were acquired from the Global Food Security-support Analysis Data (GFSAD) provided by the United States Geological Survey (USGS) at a 1 km resolution (https://lpdaac.usgs.gov/products/gfsad1kcmv001/). The wheat distribution data from 1995, 2000, and 2005 were used for further analysis.

The crop calendar map used for wheat phenology and the growing period was acquired from the Center for Sustainability and the Global Environment, University of Wisconsin-Madison (https://nelson.wisc.edu/sage/data-and-models/crop-calendar-dataset/index.php) (Sacks et al., 2010). The seeding and harvesting dates were extracted from the map and averaged for each wheat-growing zone. The major growing months for every wheat zone were used for further analysis (Table 2).

The soil-water balance is further used for water supply and demand in the Palmer drought severity index (PDSI) (Palmer, 1965). The PDSI was found to be highly correlated with the soil moisture differences within the uppermost 1 m according to site observations; thus, site observations are usually adopted to quantify agricultural droughts (Dai, 2011) but can reflect only the changes in soil moisture caused by climate change (Mu et al., 2013) and do not consider the impacts of drought mitigation measures. The PDSI dataset used in this study was acquired from the TerraClimate (http://www.climatologylab.org/terraclimate.html) dataset supported by the University of Idaho. This dataset is monthly global PDSI data covering the period of 1980–2018 at a 4 km resolution. The PDSI is calculated using precipitation and potential evapotranspiration with the Penman–Monteith equation (Van der Schrier et al., 2011; Wu et al., 2021). The PDSI ranges from −10 to 10, representing extremely dry and extremely wet conditions, respectively. We considered the PDSI drought area percentage higher than 99 % as a wall-to-wall drought and derived its occurrence times accordingly (Table 1), which means that nearly all pixels within the WGR were lower than the PDSI drought threshold. The WGRs in France, Romania, Australia and China are prone to wall-to-wall drought, while France and Romania may be related to the size of the region.

The vegetation health index (VHI) is one of the most commonly used indicators for monitoring the extent of a drought (Gomes et al., 2017; Kogan et al., 2019). The VHI reflects the actual crop stress, considers the

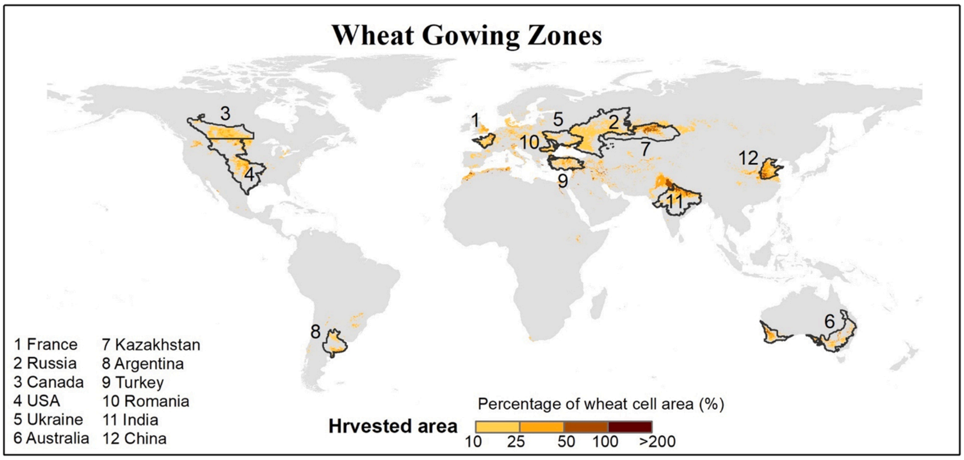

Fig. 1. Twelve major WGRs worldwide.

Table 1
Times of wall-to-wall droughts with PDSI drought-area percentages exceeding 99 %.

Zone	PDSI				Total
	1980s	1990s	2000s	2010s	
France	2	3	3	4	12
Russia	0	0	0	0	0
Canada	1	0	0	0	1
USA	0	0	0	0	0
Ukraine	0	0	2	1	3
Australia	0	1	3	1	5
Kazakhstan	0	0	1	1	2
Argentina	0	1	1	0	2
Turkey	0	0	1	1	2
Romania	3	1	4	0	8
India	0	0	1	0	1
China	1	1	1	2	5

Note: Green indicates a positive condition (less droughts), red indicates a negative condition (more droughts), and a deeper color indicates a higher degree.

local biophysical (soil, slope) and climatic conditions (García-León et al., 2019) and is strongly related to crop yield, especially in the key stage of crop growth (Kogan et al., 2012; Yang et al., 2018). The VHI dataset was acquired from the Global Vegetation Health Products (https://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/vh_ftp.php) provided by the Center for Satellite Applications and Research, National Oceanic and Atmospheric Administration, USA (NOAA STAR). This dataset is a global weekly dataset covering 1982–2018 at a 4 km resolution. The VHI can be regarded as an indicator of actual agricultural drought (Kogan, 2002). It ranges from 0 to 100, representing stressed crop conditions to good crop conditions.

The country-level yield, fertilizer and cropland irrigation data (Table 2) were acquired from FAOSTAT (FAO, 2019). The fertilizer data include nitrogen (N), phosphate (P2O5), and potash (K2O), which are converted to wheat fertilizer use based on the nutrient ratio of 200:55:252 for N, P2O5 and K2O (Roy et al., 2006).

The PDSI describes soil moisture changes that drive climate variability but does not consider the impact of human activities, such as irrigation and the planting of drought-tolerant varieties. Therefore, the PDSI can reflect agricultural drought only under natural conditions. The VHI is a remote sensing data product that monitors crop stress directly, which reflects the impact of climate variability and human activities. Therefore, the difference in the drought extent detected by the two indicators can be used to describe the effects of drought mitigation measures in alleviating drought. Here, the proportion is used instead of the actual drought-affected area to facilitate comparisons between regions. The difference in the proportion of the agricultural drought-affected area (ADAC) based on the PDSI and the VHI is calculated and aver-

Table 2
12 Yield, Fertilizer and Irrigation in Major WGRs (Countries and Regions).

Country	Regions	Growing period	Yield (tonnes/ha)				Fertilizer (kilotonnes)				Irrigation share (%)			
			1980s	1990s	2000s	2010s	1980s	1990s	2000s	2010s	1980s	1990s	2000s	2010s
France	Northwestern	March-May	5.79	6.78	6.95	6.95	2,058	1,801	1,801	1,109	8.28	12.63	13.76	14.17
Russia	North Black Sea	April-June	1.7	1.6	2.02	2.4	-	803	803	719	-	3.93	3.63	3.48
Canada	Prairie	April-June	1.83	2.27	2.44	3.16	731	819	819	1282	2.43	2.62	3.00	3.18
USA	Central Plains	March-May	2.44	2.6	2.79	3.12	6,531	7,048	7,048	7,296	14.01	14.74	15.75	16.79
Ukraine	North Black Sea	April-June	2.23	2.88	2.87	3.57	-	368	368	560	-	7.41	6.68	6.45
Australia	Southeast/southwest	September-November	1.42	1.77	1.59	1.99	293	468	468	715	8.77	11.87	10.18	8.27
Kazakhstan	Northern	April-June	-	0.86	1.06	1.14	-	37	37	42	-	9.79	8.47	7.44
Argentina	North-east	October-December	1.9	2.16	2.44	2.99	45	150	150	420	5.25	5.46	5.45	6.29
Turkey		March-May	1.94	2.04	2.26	2.69	478	579	579	728	11.96	15.44	19.96	22.03
Romania	Western Black Sea	March-May	2.85	2.61	2.59	3.72	486	157	157	163	26.67	31.30	33.19	34.12
India	Northern	Nov/Dec-March/April	1.93	2.43	2.72	3.07	2,929	4,770	4,770	8,743	26.30	31.21	37.82	41.11
China	Huanghuaihai	March-May	2.9	3.56	4.25	5.17	6,980	10,651	10,651	18,281	42.40	39.50	45.53	52.59

Note: Green indicates a positive condition, red indicates a negative condition, and a deeper color indicates a higher degree.

aged over four decades, since the 1980s, using the following equation:

$$ADAC_i = \mathrm{PA}(VHI_i < \beta) - \mathrm{PA}(\mathrm{PDSI}_i < \alpha) \quad (1)$$

where i represents the wheat-growing season, α is the threshold value for determining a drought condition using the PDSI, and β is the threshold value for determining a drought condition using the VHI; we set α as 45 and β as −0.5 (Wu et al., 2020). PA() is the proportion of cropland area affected by drought derived from either the PDSI for meteorological drought or the VHI for agricultural drought.

Waterlogging and water-borne diseases, in addition to water stress, could also lower the VHI value during the crop-growing season. Thus, only when a drought was detected with the PDSI would the VHI be used to detect whether the drought pixel represented an actual drought, which could minimize the impact of VHI anomalies caused by factors other than water stress.

3. Results

Fig. 2 shows the PDSI and the VHI values averaged over the producing area for the four decades for the 12 WGRs. As detected by the PDSI, the WGRs in Australia experienced drought in this century, and China and India experienced drought in most years, while Argentina, Canada, Kazakhstan, Russia, Ukraine, and the USA experienced wet conditions in most years. Romania and Turkey had dry and wet conditions alternatively over years, while in France, wet or dry conditions could occur in continuity.

Table 3 shows the proportion of the drought-affected area detected by the PDSI and VHI as well as their difference (ADAC), the yield coefficient of variation and the annual trend slope over the four decades for the 12 major WGRs in the world. Fig. 3 depicts the temporal development of the agricultural drought area proportion, as derived from the PDSI and VHI and their relative changes as well as from the decadal averages of the ADAC. There were regional differences in the temporal development patterns of drought among the 12 WGRs with year-to-year variability.

On average, approximately 51.4 % of the wheat-growing area suffered from natural agricultural droughts in the 2010s. After human intervention, this figure decreased to 22.9 %, with changes of 28.5 % in the 2010s increasing from 14.5 % in the 1980s. However, regional differences in the reduction in drought-affected areas were significant, ranging from 57 % to 11%, accounting for 28–55 % of drought-affected areas in the 2010s among the 12 WGRs. Although different trends of drying and wetting conditions existed over the study areas, the ADAC declined significantly in the current century compared to the first 2 decades.

3.1. Drought characteristics in 12 WGRs

In temperate climates with sufficient precipitation during the wheat-growing seasons, such as Argentina, Canada, Kazakhstan, Russia, Ukraine, and the USA, natural droughts derived from the PDSI were moderate, with affected areas less than 50 % most of the time, indicating that severe droughts do not occur frequently in these countries but occasionally, such as in 2010 in Russia and Ukraine (Loboda et al., 2017), as well as in 2018 in the USA and in 2017 in France. Canada had better agrometeorological conditions in the last decade, with only 14 % of the area affected by a severe drought. Russia and Ukraine worsened in the last decade, with more than 60 % of wheat-growing cropland suffering from water stress (Table 3, Fig. 2).

In contrast, drier areas in Australia, France, China, Romania, and Turkey suffered more severe droughts, with more than 50 % of the area affected most of the time. Australia, China and France are more vulnerable to natural agricultural drought, with maximum affected areas of 68 %, 77 %, and 72 %, respectively, over the last four decades. In the last decade, China and France have suffered severe droughts, with more than 60 % of the wheat-growing area affected. The Australian drought shifted from a moderate to a severe category at the beginning of the 21st century. France had the poorest agrometeorological conditions in the last three decades. Romania suffered a severe drought during the 2000 s (Table 3).

The WGRs in India are located in wet and warm regions (Wang et al., 2021). During the last four decades, India has been vulnerable to natural agricultural drought, affecting up to 75 % of the wheat-growing area. Recently, India suffered severe droughts in 2002, 2009 and 2012 (National Rainfed Area Authority, 2013).

An actual agricultural drought derived from the VHI is quite different from that derived from the PDSI. Overall, approximately 23 % of the wheat-growing area was actually affected by drought over the last four decades, showing a reduction from 29 % in the 1980s to 23 % in the 2010s. Australia was most affected by drought in the 21st century, with

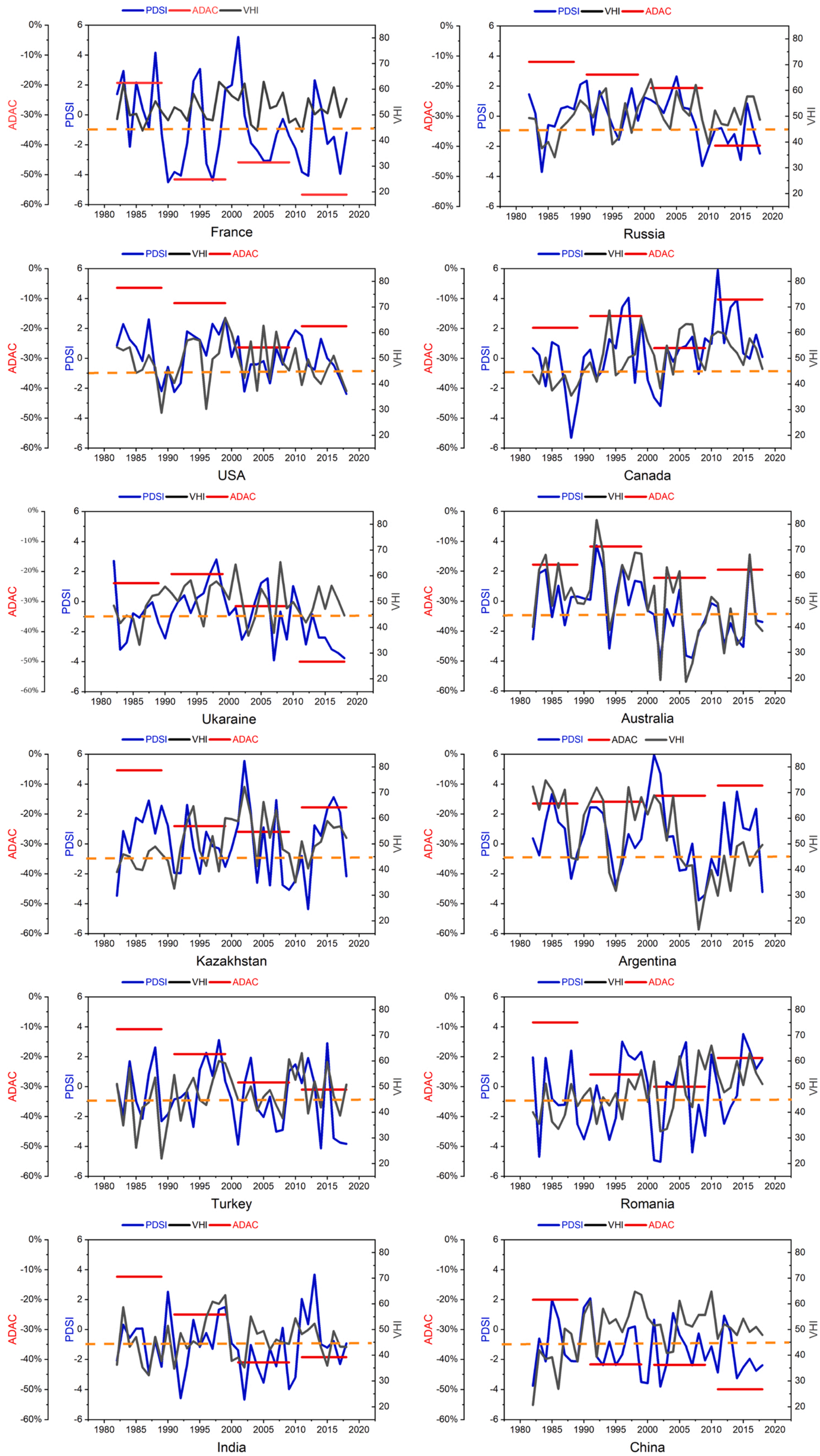

Fig. 2. Average PDSI and VHI Values and ADAC over the Four Decades for the 12 Wheat-Producing Regions.

Table 3
Proportion of Drought-Affected Areas Derived from the PDSI and VHI as well as the ADAC, Yield Coefficient of Variation and Annual Trend Slope over the Four Decades for the 12 Major Wheat-Producing Regions.

Zone	PDSI (%)				VHI (%)				ADAC (%)					Yield CV (%)				Yield trend (tonnes/ha/year)			
	1980s	1990s	2000s	2010s	1980s	1990s	2000s	2010s	1980s	1990s	2000s	2010s	RR	1980s	1990s	2000s	2010s	1980s	1990s	2000s	2010s
France	27.64	67.58	60.43	72.26	8.33	15.99	14.55	15.14	-19.31	-51.59	-45.88	-57.12	-79	9.08	5.86	6.87	10.88	0.126	0.097	0.023	-0.05
Russia	40.09	29.26	30.14	61.70	28.16	13.09	9.50	25.17	-11.93	-16.17	-20.64	-36.53	-59	-	12.15	10.28	16.36	-	-0.025	0.028	0.134
Canada	55.81	28.12	42.50	14.11	36.04	12.25	15.93	2.97	-19.77	-15.87	-26.57	-11.14	-79	17.34	6.82	14.92	9.24	-0.007	0.032	0.1	0.052
USA	31.05	33.34	44.31	44.64	24.64	21.79	17.99	27.25	-6.41	-11.55	-26.32	-17.39	-39	6.83	7.83	8.16	6.49	-0.015	0.051	0.046	0.035
Ukraine	53.97	25.68	53.48	72.77	32.55	27.00	5.66	23.17	-21.42	1.32	-47.82	-49.6	-68	-	19.71	12.65	12.88	-	-0.166	-0.016	0.136
Australia	38.36	24.5	67.62	63.42	20.57	12.77	45.43	45.91	-17.79	-11.73	-22.19	-17.51	-28	19.21	16.35	28.99	12.4	0.052	0.042	-0.048	0.025
Kazakhstan	19.15	46.26	43.05	39.33	13.76	22.21	17.08	22.29	-5.39	-24.05	-25.97	-17.04	-43	-	32.85	16.55	20.32	-	-0.013	-0.012	-0.003
Argentina	28.01	31.26	43.76	37.05	11.51	15.36	29.86	25.69	-16.50	-15.9	-13.9	-11.36	-31	10.01	10.31	11.69	10.54	-0.019	0.048	0.025	-0.013
Turkey	48.67	33.03	59.61	51.09	37.89	13.92	30.96	22.42	-10.78	-19.11	-28.65	-28.67	-56	7.68	7.53	7.18	5.13	0.023	0.012	0.045	0.012
Romania	45.40	49.79	53.29	24.66	36.89	23.82	23.26	6.52	-8.51	-25.97	-30.03	-18.14	-74	16.49	15.74	24.89	18.72	0.108	0.021	0.012	0.246
India	50.85	48.25	74.94	58.44	38.49	23.26	33.94	17.94	-12.36	-24.99	-41.00	-40.50	-69	8.73	6.34	3.75	5.87	0.056	0.045	0.019	0.024
China	60.44	57.59	65.39	76.99	40.39	15.91	23.58	25.76	-20.05	-41.68	-41.81	-51.23	-67	7.09	8.13	9.13	4.56	0.062	0.079	0.126	0.092
Total	43.55	36.92	51.13	51.36	28.94	15.40	22.94	22.88	-14.61	-21.52	-28.19	-28.48	-55	-				-			

Note: Green indicates a positive condition, red indicates a negative condition, and the darker the color is, the greater the corresponding value. PDSI = Palmer drought severity index, VHI = vegetation health index, RR=relative reduction in drought-affected areas in the 2010s

more than 45 % of the wheat area being affected. In other regions, less than 25 % of the wheat area was affected by drought during the last decade. This shows that the actual agricultural drought area is less than the natural drought area even without human interventions.

3.2. Drought mitigation in 12 WGRs

The extent of the reduction in the agricultural drought-affected area (ADAC) varied among the 12 WGRs. The ADAC decreased from −14.6 % in the 1980s to −28.5 % in the 2010s globally. During the last decade, the absolute reductions in the ADAC for China, France, and Ukraine were 50 %, 57 %, and 49.6 %, respectively, higher than those for other places, followed by India (−40.5 %) and Russia (−36.5 %). China and France have had greater ADAC reductions since the 1990s. The reduction in ADAC was low in India, Russia, Turkey, Ukraine, and the USA in the last century but has improved recently, meaning that the drought-resilience capacity has improved in these regions. Russia and Ukraine experienced a 20 % decrease in the drought-affected area during the last decade compared with the preceding decade. For Argentina and Canada, this change was very low over the last four decades, only approximately −11 % in the last decade, indicating weak capacities in adapting to the negative influences of agricultural droughts.

Fig. 2 shows the time series of the drought-affected area for the 12 major WGRs. The drought-affected area derived from the PDSI departed gradually from the VHI. These departures occurred in China in 1991, India in 2001, Romania in 2007, Russia in 2005, and Ukraine in 2012, and the departures amplified gradually; there was no obvious departure in other countries.

Actual agricultural drought conditions in China and India have improved since 1984 and 1987, respectively. The PDSI shows that China had the poorest agrometeorological conditions in 2000 and India in 2002, but the VHI detected these conditions or agricultural droughts with significantly different success rates. The NDVI has remained stable since the 1980s, and fertilizer use and yields have strong increasing trends. This leads to the inference that the wheat yield had a significant relationship with the ADAC. Since 1980s, China and India experienced a sharp increase of fertilizer use and built large areas of irrigation system, which helped mitigating the impact of drought. Turkey had a trend similar to China's and showed a gradual improvement in drought conditions, as supported by the NDVI, fertilizer-use, and yield trends (2.13 % per year).

Australia's drought resilience has remained largely unchanged since the 1980s, with ADAC ranging between 11 % and 22 %. Australia experienced a severe drought, with more than 63 % of the area being affected by a natural drought and 45 % of the area being affected by an actual drought in the beginning of the new century. The yield trend agreed with the trend in the drought-affected area (0.56 % per year) rather than with those in the NDVI and fertilizer use.

France faced the poorest agrometeorological conditions during the last four decades (Table 1, Fig. 3) and showed no improvement as determined by the PDSI analysis. At the same time, the drought-affected area, as determined by VHI analysis, has decreased since the beginning of the 1980s, with a maximum ADAC value of 57 %. The development of water saving irrigation and rainwater recycling technology has helped reducing the impact area of actual agricultural drought. A positive trend for NDVI and a negative trend for fertilizer usage were also observed. The increase in wheat yields agreed with the trends in the reductions in drought-affected areas in France (2.86 % per year).

Russia and Ukraine have had similar trends since the 1990s. During the last decade, the drought-affected area, as determined by the PDSI analysis, was 62 % for Russia and 73 % for Ukraine. However, these percentages changed to 25 % and 23 %, respectively, when VHI analysis was used, leading to changes of −36.5 % and −49.6 %, respectively. Data for Russia showed that since 2005, there has been a marked increase in the drought-affected area as derived from the PDSI analysis, which indicates poor agrometeorological conditions in general. At the same time, the drought-affected area, as determined by the VHI analysis, has decreased since 2010. A positive trend was observed for NDVI since 2004 and for fertilizer usage since 2010. All of these observations agreed well with the increase in wheat yields, which suggests that the main factor causing yield changes in Russia was the reduction in the drought-affected area rather than the poor agrometeorological conditions (a significant reduction of 2.80 % per year). Ukraine has had a very significant improvement since the 2000s (2.11 % per year). Kazakhstan and Romania, similar to Russia, have had a significant improvement in drought mitigation since the 1990s, but the mitigation effect has declined in the last decade as a result of improved agrometeorological conditions.

WGRs in the United States have been less affected than those in other regions by both natural agricultural drought and actual drought, with less than 45 % and 28 % of the affected areas, respectively, over the past four decades. In the 1980s, the proportion of drought area decline was only 6.4 %, but it was 26 % in the 2000s and 17 % in the 2010s. Compared with the other regions, the improvement in drought conditions in the United States is relatively low. The wheat yield trend agreed more with the reduction in the drought-affected area (1.77 % per year) than with other factors, such as NDVI or fertilizer use.

Argentina and Canada are the two countries that showed no

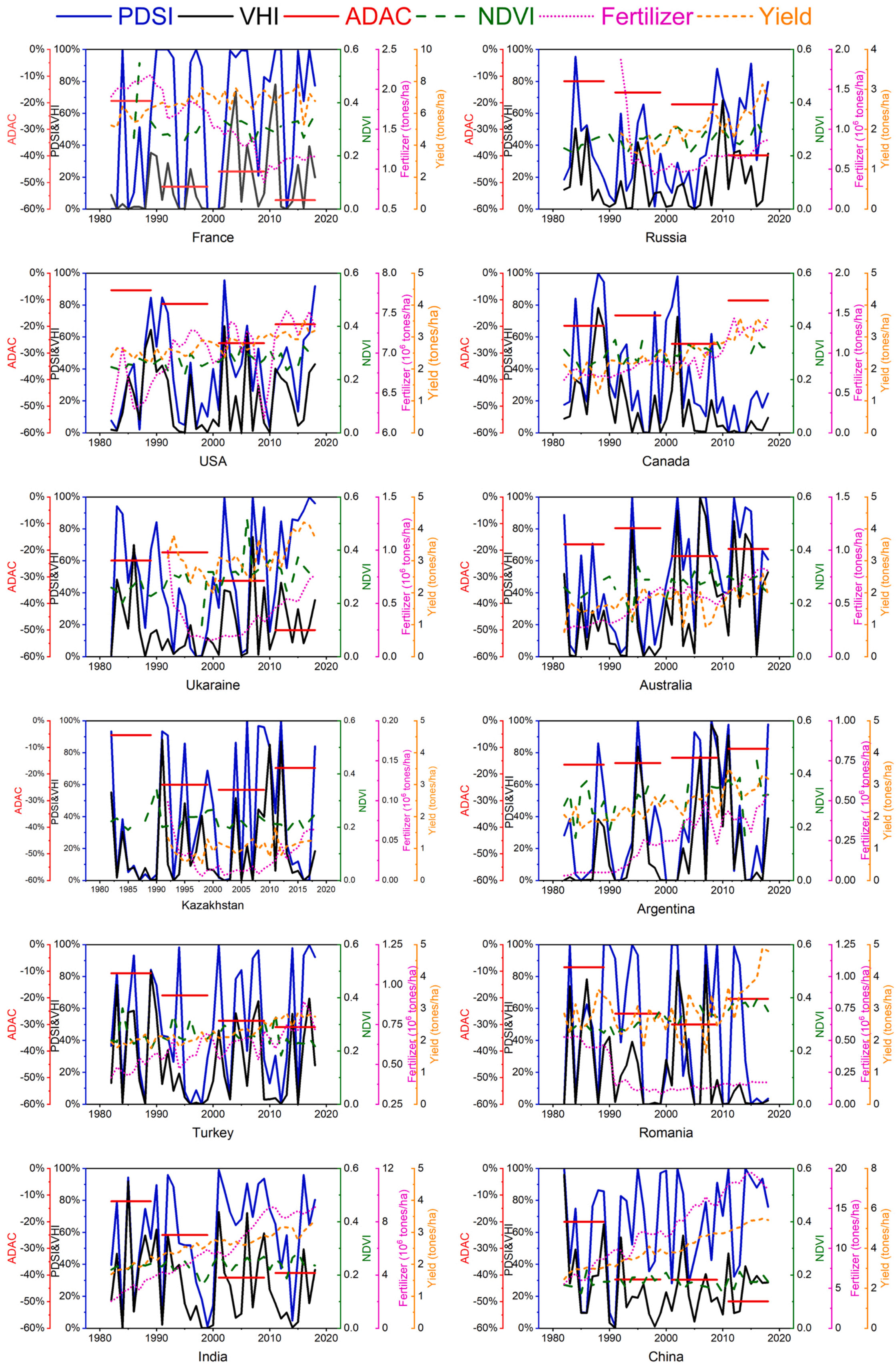

Fig. 3. The Proportion of Agricultural Drought-Affected Area Derived from PDSI and VHI, NDVI, Fertilizer use, Wheat Yield and ADAC over the Four Decades for the 12 Wheat-Producing Regions.

improvement in drought conditions over the last four decades, with ADAC being less than 16.5 % and 26.5 %, respectively. Argentina is the only country for which ADAC has increased since the 1980s, meaning that the drought mitigation or adaptation impact has been on a downward trend. In fact, the crop-growing season is not prone to drought, which causes a lower VHI value (Fig. 3).

The wheat yield variability in Kazakhstan is the highest among WGRs, with a CV of 20.3 % in the 2010s and has remained at a high level since the 1990s, followed by the values in Romania, Russia, Ukraine, Australia, France and Argentina, with CVs greater than 10 % in the 2010s (Table 3). Interannual variability in wheat yields increased with increasing ADAC, although not significantly, for the 12 wheat-growing zones collectively (Fig. 4). In the 1980s, the yield variability did not increase with ADAC, but it increased significantly in the 1990s and the 2000s. This increasing trend slowed down in the 2010s, when the regions experienced more severe droughts than in the preceding decades.

Table 4 listed the correlation between PDSI, VHI and ADAC derived drought areas. PDSI and VHI for each decade is calculated as average. The bold numbers represent significant correlation, PDSI have a significant positive correlation with VHI and significant negative correlation with ADAC during most periods, while VHI and ADAC has quite unsignificant correlation, which indicates that ADAC is more influenced by PDSI as meteorological drought is the largest influential factor on ADAC. The nonsignificant correlation between VHI and ADAC is also an indicator that there exists large divergence between all 12 WGRs, which is consistent with previous results.

3.3. Mitigation of extreme droughts

Extreme droughts occurred in Russia in 2010, the USA in 2018, France in 2012, China in 2009, and India in 2002 (Table 5). Russia experienced its most severe drought during the last half century in 2010; this drought caused Russia's wheat yield to be 14.6 % lower than the 1992–2018 trend and 17.2 % lower than the yield in the previous year (FAO, 2019; Wegren, 2011), and only 10.5 % (ADAC) of drought-affected areas were alleviated, indicating the poor effects of drought mitigation (Fig. 5a). Drought coverage derived from the PDSI peaked at 63.5 % in the USA in February 2018, the actual agricultural drought was severe, with a VHI value of 37.2, and approximately 28.4 % (ADAC) of drought-affected areas were mitigated, leading to a 3.9 % reduction in wheat yield in 2018 compared with that in 2017 (http://cloud.cropwatch.com.cn/) (Fig. 5b). In the spring of 2012, a severe drought occurred in France. France employed adequate drought mitigation measures, bringing relief to approximately 94.5 % (ADAC) of the drought-affected area, and FAO statistics suggested that French

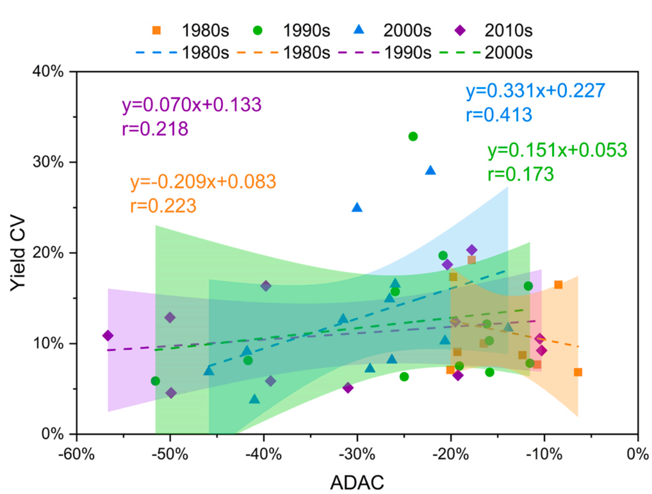

Fig. 4. Relationship between ADAC and the Wheat Yield Coefficient of Variation during the Four Decades.

Table 4
Correlation between PDSI, VHI and ADAC derived drought area percentage.

	PDSI and VHI		PDSI and ADAC		VHI and ADAC	
	Pearson's r square	slope	Pearson's r square	slope	Pearson's r square	slope
1980s	**0.72****	**0.77**	0.23	-0.22	0.00	0.01
1990s	0.08	0.01	**0.84****	**-0.79**	0.00	0.09
2000s	**0.48***	**0.53**	**0.41***	**-0.46**	0.01	0.07
2010s	**0.43***	**0.37**	**0.72****	**-0.70**	0.03	-0.27

wheat yield increased by 7.4 % compared with that in 2011 (Fig. 5c), indicating that wet conditions instead of drought cause crop stress in the WGR of France (Ben-Ari et al., 2018). In China, the 2009 drought influenced 6.04 million hectares of crops (Zhang et al., 2012). The PDSI drought area was 91.1 % for wheat-growing cropland, and the actual drought area was decreased by 71.9 % (Fig. 5d), which led to a wheat yield reduction of 0.48 % compared to 2008. Owing to a 21.5 % deficit in seasonal rainfall, India experienced a major drought in 2002 (Bhat, 2006). More than 86 % of the wheat-growing area was influenced, but 51.89 % was successfully protected from drought (Fig. 5e), with a wheat yield 1.99 % higher than that in 2001. Fig. 6 shows the relation of ADAC and wheat yield changes over 5 extreme drought events. China, the USA, and India had similar wheat yield change percentages under different ADAC levels. Based on nonstatistic yield data (Fig. 6b), the ADAC is significantly correlated with yield changes during extreme drought events. It is worth noting that in contrast to the decade analysis the ADAC has a low correlation with the yield CV (Fig. 4), and the ADAC reflects the drought mitigation effects independent of yield increasing measures; the purpose of drought mitigation measures in extreme drought years is to stabilize yield changes from previous normal years. The high correlation of ADAC to yield changes in extreme years meets the expectations of the major purposes of drought mitigation measures.

4. Discussion

Agricultural drought is the result of natural water variability, climate change, human activities, and microclimate condition changes due to changes in land and water management (AghaKouchak et al., 2021). Therefore, there are significant regional differences in drought characteristics and performances of drought mitigation measures. Traditionally, assessment of the performance of drought mitigation measures attempts to describe the effect of a measure in isolation, usually observing the changes and results before and after implementation, using yield and/or water productivity. Due to the compounding feedback that governs drought state and behavior, it is difficult to quantitatively evaluate the effect of a drought mitigation measure and determine which measure plays a leading role, but through regional comparison, it is possible to understand which region performs better and determine which measures or combinations thereof work. Using the changes in the proportion of cropland areas affected by drought derived from the PDSI and VHI, we analyzed the performances of the drought mitigation measures for 12 major WGRs of the world. It was found that the mitigation measures have not fully alleviated the impact of drought in these WGRs. The proportion of drought-affected area decreased by approximately 28.5 % globally, accounting for 55 % of the drought-affected area, and drought mitigation efforts have steadily succeeded, with the absolute ADAC increasing from 14.5 % to 28.5 % over the past four decades. The VHI analysis revealed that drought still persists in approximately 22.9 % of the WGRs.

Whether an onset of a drought event would cause a disaster for wheat growth depends on both the severity of the event and the vulnerability of the ecosystems experiencing it (Lesk et al., 2016). We have found that there are large regional variabilities in the performance of drought mitigation efforts. For all 12 regions studied, the adaptation or mitigation schemes were more effective in combating droughts in China, India

Table 5
Drought indicators of country-level severe drought cases.

Region	Year	Mean value		Drought affected area (%)		ADAC (%)
		PDSI	VHI	PDSI	VHI	
Russia	2010	-2.10	39.25	70.19	59.70	-10.49
USA	2018	-2.38	37.20	91.88	63.48	-28.39
France	2012	-4.08	56.49	100.00	5.49	-94.51
China	2009	-2.07	55.65	91.08	19.24	-71.85
India	2002	-4.67	35.19	86.45	34.56	-51.89

Note: Green indicates a positive condition, red indicates a negative condition, and a deeper color indicates a higher degree.

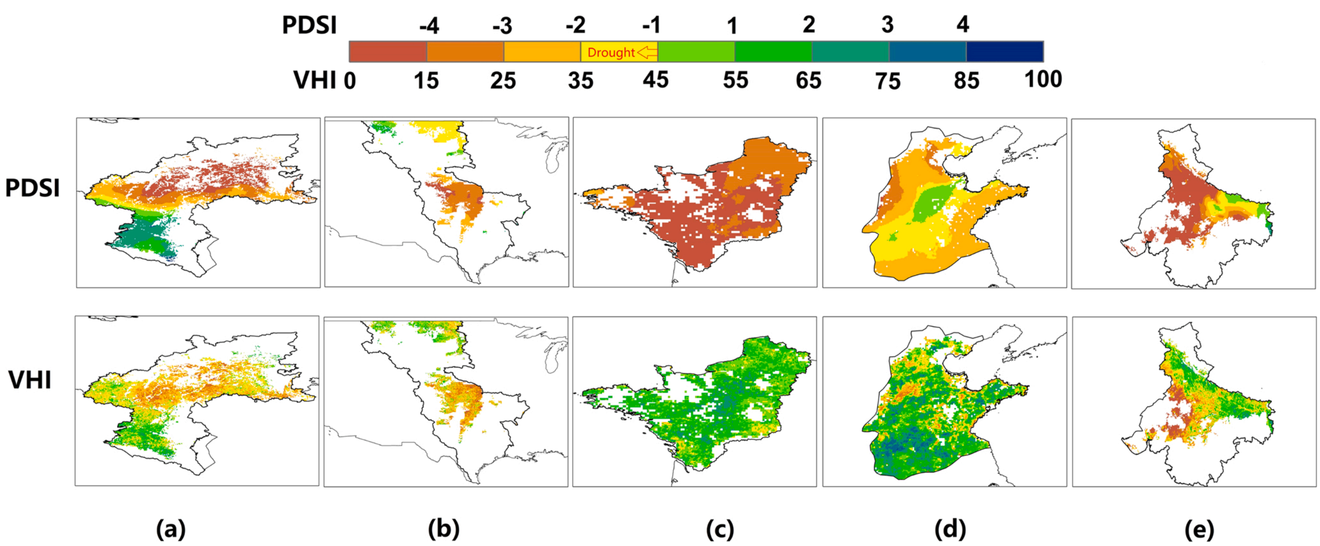

Fig. 5. Drought Extent Derived from the PDSI (above) and VHI (bottom): (a) Russia, (b) USA, (c) France, (d) China, (e) India.

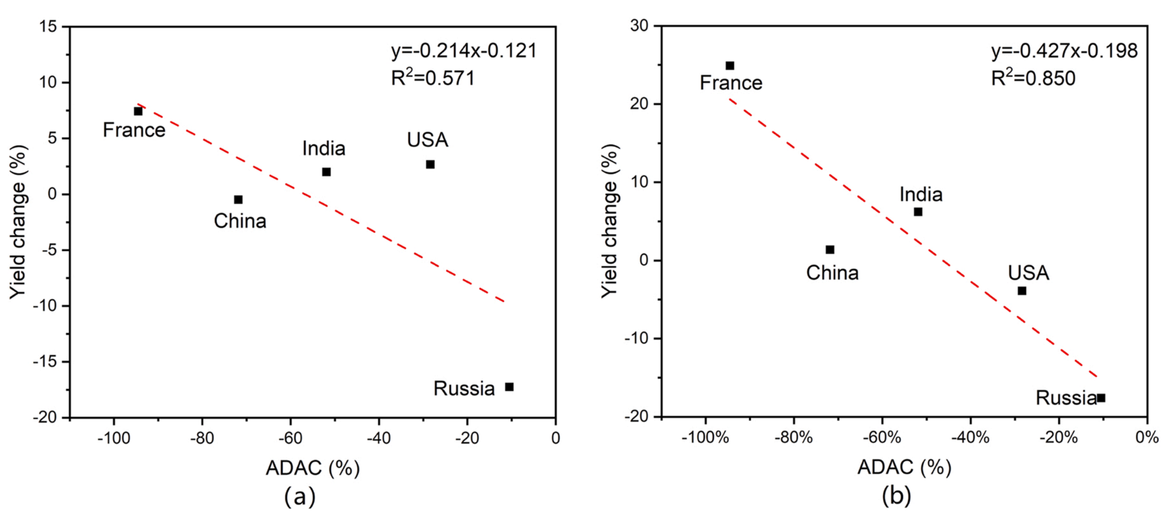

Fig. 6. The Relation of ADAC and Wheat Yield Changes over 5 Extreme Drought Events: (a) Yield Data from FAO Statistics, (b) Yield data from Nonstatistic Sources: Russia, France and China from Iizumi et al. (2014), USA from CropWatch and India from Ray et al. (2015).

and France; Argentina and Canada apparently did not show improvements (Table 3). In addition, different temporal trends were observed. While Turkey, Russia, China, and India have shown continuous improvement in their drought mitigation performance during the last four decades, Australia and Canada have not exhibited any improvement, and Argentina's performance has even worsened. These regional variations in drought mitigation performance could be a combined result of varying drought mitigation measures and climate conditions prevalent in different regions.

The relationship between ADAC and wheat yield variation is positive, although not significant in the decade period (Fig. 4), but significant at extreme drought events (Fig. 6), which suggests that the wheat yield and variations are not good indicators to assess the effectiveness of drought mitigation schemes. Some measures, such as irrigation, could improve wheat yield (Hornbeck and Keskin, 2014; Suarez et al., 2019; Zaveri and Lobell, 2019) and change drought characteristics since irrigation stabilized the climate extremes and variability, which led to yield reductions in rainfed crops but not irrigated crops (Troy et al., 2015); the same benefits apply for mulching and water conservation measures (Uwizeyimana et al., 2018; Yan et al., 2015) and increases in planting density (Li et al., 2020; Solh and van Ginkel, 2014). Some measures, such as the development of new varieties of crops (Qin et al., 2015b; Simtowe et al., 2019) and the use of fertilizers, pesticides (Xiao and Tao, 2014) and small-farming practices (Burrell et al., 2017; Dobler-Morales and Bocco, 2021), could improve yield without directly changing drought characteristics. Therefore, the changes in drought characteristics should be used to assess the performance of drought mitigation schemes (Wu et al., 2020). This approach can avoid confusion between drought mitigation performance and wheat yield improvement.

4.1. Drought mitigation measures in dryland areas

Dryland wheat is more vulnerable to drought than irrigated wheat (Daryanto et al., 2016). Under drier conditions, irrigation is the first choice in combating drought (Yin et al., 2020; Zaveri and Lobell, 2019). As detected by the PDSI, WGRs in Australia, China and India experienced drought in most years, which required annual irrigation, while those in France, Romania and Turkey required intermittent irrigation since drought alternated over years. Regions without irrigation suffered more yield losses than regions with irrigation (Lesk et al., 2016). The yield difference between rainfed or dryland and irrigated wheat was 34 ± 9 % globally (Wang et al., 2021). Water availability for wheat can be further improved by rainfall water harvesting – by collecting rain water in on-farm reservoirs or catchments for later use by crops (Biazin et al., 2012).

China and India have steadily improved their drought mitigation capacity and yield variability since the 1980s. The relevant investment and policy interventions have helped expand irrigated areas steadily during the last four decades, even under strained water availability (Zhou et al., 2020). China's total irrigated area and the annual irrigation water consumption increased by 10.2 % and 29.74 %, respectively, between 1982 and 2015. The irrigated area increased mainly for wheat produced in northern China (Yin et al., 2020), where the irrigation rate was 76 %, the highest among the 12 WGRs; additionally, nearly 70 % of irrigation was based on groundwater resources (Wang et al., 2019), which led to overexploitation (Qiu, 2010). In addition, the Chinese government has enhanced its efforts to encourage farmers to adopt water saving technologies, which improve irrigation efficiency and management policies. All of these measures have increased capabilities to better deal with the increasing water scarcity and support the growth of wheat production in China.

In India, there has been a constant focus on improving drought mitigation measures, such as expanding irrigation and rainwater harvesting, developing small reservoirs or village ponds, and improving soil conservation and waste water recycling for irrigation (Rao and Gopinath, 2016). For decades, the Indian government's policy has been to expand irrigation to cope with drought and thus improve agricultural productivity. Although the area under wheat cultivation remained stable between 1966 and 2009, the irrigated area increased rapidly (Zaveri and Lobell, 2019), with a current irrigation rate of 41 % in the WGR.

Although Australia suffered severe drought conditions, its irrigated area of cropland remains only 8.3 % (Table 2). Previous studies have shown that the adoption of new drought-resistant wheat varieties and better crop-rotation techniques and the application of optimum fertilizer rates caused wheat yields to almost double between 1980 and 2011 (Burrell et al., 2017). In addition, changes in farming practices apparently decoupled NDVI trends from rainfall patterns in western Australia (Burrell et al., 2017), which was confirmed by the improvement in yield variability. However, the currently high level of yield variability suggests (Table 3) that Australia needs to implement more measures to combat drought.

Dry and wet conditions alternate over the years in the WGR of Romania. The high yield variability can be explained by the soil moisture availability from April-May and then from November-December (Lecerf et al., 2019). The high variability in wheat yield in Romania, with a CV of 24.89 % in the 2000s and 18.72 % in the 2010s (Table 3), ranking second after that in Kazakhstan, indicates that more drought mitigation measures are needed.

While irrigation has been used as an effective tool for reducing drought impacts, dwindling water resources in some regions (Elliott et al., 2014) cast doubt on the feasibility of irrigation to continue to increase wheat yields on a global scale. Groundwater abstraction has already exceeded the sustainable yield in many aquifers, such as the High Plains in the USA (Scanlon et al., 2012; Wada et al., 2012, 2010), North China Plain (Qiu, 2010) and India (Famiglietti, 2014). Therefore, when using irrigation as a short-term drought mitigation measure, it is necessary to consider the limits of the amount of groundwater available (Wu et al., 2014) and to explore other measures to enhance drought resilience.

Mulching is used as an alternative method to mitigate drought stress. Mulching, which includes covering the soil surface with cover crops, crop residues, or plastic films, prevents water losses from soil, reduces soil-water evaporation, helps preserve root-zone moisture during the drought period (Liakatas et al., 1986), and improves crop defenses against annual and seasonal droughts even in relatively humid regions (Sun et al., 2020). China is the largest cropland mulching country (Lal, 2018). The use of plastic-film mulching in agriculture has greatly increased from 6 thousand tons in 1982–2.5 million tons in 2018, representing a 400-fold increase (Changrong et al., 2014). The area of cropland covered with mulch increased from 0.12 Mha in 1982–4.9 Mha in 1991, 11.0 Mha in 2001 and 17.7 Mha in 2018 (National Bureau of Statistics, 2018). Among the major wheat-growing provinces in China (Hebei, Henan and Shandong), the mulch-covered cropland area currently exceeds 0.7 Mha. In 2012, 13 % of China's cropland was mulched, which accounted for nearly 60 % of the global mulched area. Mulching has increased yields by approximately 20 % globally (Qin et al., 2015a) and by approximately 18 % in China (Tan et al., 2019) and has reduced evaporative water loss by approximately 3 % on the North China Plain (Yan et al., 2015). Crop yield increased 77.9 % under full mulching and 38.9 % under partial mulching. Irrigation and mulching practices have helped China reduce yield variability. Conservation agriculture has also been applied to wheat crops under a rice/maize–-wheat rotation on the Indo-Gangetic plains (Bhan and Behera, 2014), resulting in India achieving the second-lowest yield variability.

4.2. Drought mitigation measures under wet conditions

Temperate zones usually experience sufficient precipitation during wheat-growing seasons and infrequently suffer water stress. Therefore, irrigation is not considered essential and is not a key factor contributing to obtaining good yields even after mild droughts occur. Argentina, Canada, Kazakhstan, Russia, Ukraine, and the USA have relatively low percentages (less than 17 %) of irrigated lands (Table 2). Yield anomalies between irrigated wheat and dryland/rainfed wheat were not significant in the USA, which means that irrigation was not an effective tool to improve wheat's ability to withstand climate risks in the central United States (Zhang et al., 2015). Although large-scale irrigation development may be unrealistic due to significantly increased fertilizer use since the late 1990s (Swinnen et al., 2017), Ukraine and Russia had relatively high drought mitigation capacity, with absolute ADAC exceeding 49.6 % and 36.5 %, respectively, during the 2010s, while regions in the other four countries had lower absolute ADAC values, less than 17.4 % for the USA in the 2010s (Table 3).

During dry conditions, which sometimes occur, wheat yield depends on soil moisture reserves. Therefore, conserving soil moisture is one of the major drought mitigation measures. There are a number of methods that can be used to conserve soil moisture (Bhan and Behera, 2014; Kosmowski, 2018; Qin et al., 2015a; Zipper et al., 2015), such as mulching, which relies on providing some kind of cover for the soil to reduce evaporation and prevent soil exposure to direct sunlight (Yan et al., 2015). In addition, the methods used for improving soil quality and conservation will help conserve soil moisture and thereby mitigate droughts.

The conservation-tillage practice, where the crop residue is left on the soil to reduce evaporation and protect the soil surface from wind erosion, direct sunlight and heavy rain impacts, increases the soil's capacity to absorb and retain water. Water conservation is also possible by minimizing soil disturbance and reducing nonbeneficial evaporative water loss from the soil surface (Stagnari et al., 2014). Canadian and US farmers have improved their drought resilience or mitigation measures over time. These measures include developing and adopting drought-tolerant crop varieties, implementing no-till sowing and fallowing, and leaving crop residues after the harvest (Wallander et al., 2013). Drought mitigation measures used in the United States include developing an early warning system for drought, developing drought-resistant varieties, improving irrigation efficiency, enhancing drought resilience, and improving the soil-moisture holding capacity (Wallander et al., 2013). In the USA, the use of agricultural plastic increased from 0.2 million tons in 1994–0.5 million tons in 2001 (Lawrence, 2007), and nearly 28.8 % is used for plastic mulching. The relatively low yield variability suggests that drought impacts have been minimized in the WGR of the USA. Similar measures have been applied in other regions (Birthal and Hazrana, 2019; FAO et al., 2018; Gleeson et al., 2020). For example, in western Europe, 0.5 million tons of plastic mulch was used in 1997 (Kasirajan and Ngouajio, 2012).

A higher groundwater table may also help mitigate the impacts of drought on wheat production since wheat can access water from a higher groundwater-saturated zone during drought conditions (Zipper et al., 2015). In such regions, groundwater exploitation is limited if no or less irrigation is applied, such as in Russia, Argentina, Ukraine and Canada.

4.3. Improving drought resilience

Improved farmland management practices also help create a better drought-resilient wheat production system. These practices may include early seeding and filling seedlings in time, using a controlled-tile drainage system (Sunohara et al., 2016), accessing drought-early warning information, and buying crop insurance (Li et al., 2018). These practices are commonly used in Australia, Russia, Ukraine, and the USA (Burrell et al., 2017; Wallander et al., 2013). Continued advances in plant breeding and genetics for developing more drought-tolerant crops will also contribute to reducing drought vulnerability (Manavalan et al., 2009; Varshney et al., 2018). Most of the wheat varieties currently cultivated in Russia are the same as those used 20 years ago. However, it is difficult to find comparable practices for the 12 WGRs included in this study.

Only a small share of the wheat-cultivated area was irrigated in France, and this area increased from 8.28 % in the 1980s to 14.17 % in the 2010s (Table 2). Another study showed that only 1.3 % of the area was irrigated in 2000, increasing to 3.6 % in 2010 (Loubier et al., 2013). However, absolute ADACs were higher than 45.9 % in the last three decades, and wheat yields have improved significantly since the 1980s, indicating that the WGR in France has a strong ability to withstand climate threats. Previous studies have shown that heat and water stress indices are not directly related to wheat production anomalies, and French wheat production can be more negatively affected by excess water than by droughts (Zampieri et al., 2017). The combination of abnormally warm temperatures in late autumn 2015 and abnormally wet conditions in the following spring led to its most extreme wheat yield loss in 2016 (Ben-Ari et al., 2018). Dry spring conditions generally have a positive impact on wheat, with a lower possibility of disease (Lecerf et al., 2019). Therefore, it seems that the WGR in France is tolerant to drought impacts. Determining what factors played a role in reducing the drought impact requires further study and will help other regions design drought mitigation schemes.

Social stability and changes in land-tenure systems might explain the regional variation in the magnitude of success of drought mitigation efforts. The drought mitigation efforts introduced in the 1990s have steadily succeeded in the “transition countries” of Russia, Ukraine, Kazakhstan, and Romania. The changes in the land-tenure system and the increased amount of fertilizer use can partially explain the reasons for improved drought resilience in Russia and Ukraine. Since 2005, the Russian government has also increased subsidies (Liefert and Liefert, 2012). Institutional reforms have helped to overcome institutional constraints in major food-producing areas (Swinnen et al., 2017). After a series of rural reforms were introduced in China in the 1980s, the impact of drought mitigation measures has significantly magnified and has remained high ever since.

Farm size has also played a critical role in agricultural sustainability (Ren et al., 2019). China's agriculture is characterized by a small-scale farming system, with an average farm size of less than 1.2 ha, while the average farm size in many developed countries is much larger, approximately 40 ha in France and 180 ha in the USA (Adamopoulos and Restuccia, 2014). Operating scales also affect the feasibility of adopting drought mitigation measures. Nevertheless, the relationships between social systems and the overall drought mitigation measure and the possibility of their adoption are far from being well understood individually; therefore, overall assessment is recommended.

Improving the drought resistance capability from wheat physiological characteristics is another effective drought mitigating method, including breeding and use of osmolyte. Breeding of drought-tolerance wheat has grown to be a rapid transregional measure to increase drought mitigation ability (Khan et al., 2019). Based on applying genetic modification, recent drought-tolerance wheat species have deeper larger root and lower transpiration from reduced leaf size and smaller stomatal conductance, which exhibits stronger drought tolerance capability in dryland environment (Khadka et al., 2020; Li et al., 2021). Considering the rapid effects of wheat breeding, Argentina has approved drought tolerance wheat species in 2020 and the mitigation effects remains to be seen. By rapid breeding and cultivation, drought tolerant wheat seeds could be transported and quickly distributed to farmlands under drought threats. With good characteristics of drought resistance, wheat breeding method has the potential to achieve higher benefits than other mitigation methods. Osmoregulation helps crop to sustain water withdraw capability from low water potential environment and can enhance drought tolerance of wheat (Ashraf et al., 2011). Exerting exogenous various compounds, such as organic osmolytes has gained great attention as it's more efficient and quick than breeding to improve drought tolerance of crops and reducing the damage caused by drought.

5. Conclusions

Our study compared the performances of drought mitigation measures practiced in 12 major WGRs of the world and their evolution over the last four decades. This study performed spatially and temporally coherent change analyses of drought characteristics with or without human intervention. The study confirms that the changes in drought characteristics can be used to explain the performance of drought mitigation schemes, eliminating confusion of yield improvements. The results suggest that the drought-affected area in the study regions has decreased by approximately 28.5 %, accounting for 55 % of the drought-affected area, with significant regional differences ranging from 28 % to 79 % in the 12 WGRs. Drought mitigation measures succeeded in reducing the percentage of the drought-affected area from 14.5 % in the 1980s to 28.5 % in the 2010 s. Among all regions considered in this study, the drought mitigation measures practiced in China and India are the most effective in combatting droughts, followed by France and Ukraine. The percentage of drought-affected area changed only slightly in Argentina and Canada, where wheat is not prone to droughts. Irrigation should be used as a drought mitigation tool in dryland areas. Water conservation measures are suitable for both dry and wet areas. France and Ukraine are good examples to be followed. To comprehensively quantify the impact of drought mitigation measures in WGRs, the change in drought characteristics is a good indicator to assess the performance of the combination of drought mitigation measures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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