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Agricultural and food security impacts from the 2010 Russia flash drought

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ABSTRACT

The flash drought and its associated heat wave that affected western Russia in the summer of 2010 had significant cascading agricultural and socioeconomic impacts. Drought indicators sensitive to soil moisture and evapotranspiration (ET) showed that the flash drought began in June 2010, then intensified rapidly and expanded to cover much of western Russia. By early July, almost all of the major wheat producing regions of Russia were experiencing extreme water stress to the winter and spring wheat crops. The timing of the onset of the flash drought was particularly devastating as the period of most rapid intensification overlapped with the flowering stage for both the winter and spring wheat crops. As a result, wheat yields in Russia were reduced by over 70 percent in top wheat producing oblasts and total wheat production was reduced by 20 million metric tons (MT) compared to the previous seasons. In fulfillment of its recently adopted Food Security Doctrine, the Russian government banned the export of wheat in early August 2010 to preserve wheat for its own consumption. Further compounding matters on a global scale, the significant reduction in wheat production in Russia coincided with wheat production issues in places like western Australia, which led to a large drop in global wheat stocks. The sharp drop in global wheat stocks coincided with a rapid increase in wheat prices across the globe. The rapid increase in wheat prices, partly resulting from the rapid intensification of drought in Russia, led to increased prices for wheat flour and bread in many countries throughout the world. This ultimately led to an increase in poverty and civil unrest in countries like Mozambique and Egypt with a history of inequality and poverty.

1. Introduction

The 2010 heat wave across western Russia was an extreme climate event that led to profound environmental, economic, and societal impacts. For historical context, the summer of 2010 was likely the warmest for western Russia in the last half millennium (Barriopedro et al., 2011) and the drought was the worst in the last century (Welton 2011). While evidence is not fully conclusive as to how great a role climate change played in driving conditions in the summer of 2010 in Russia, Rahmstorf and Coumou (2012) found there was an 80% chance that the event was directly linked to climate change by using Monte Carlo simulations. Daily record high surface temperature values exceeding 32°C were reached for Moscow and the surrounding region by mid-to late-July and persisted until the second week of August (Barriopedro et al., 2011; Grumm and R H, 2011).

A flash drought is a drought that develops and intensifies more rapidly than usual (Otkin et al., 2018) and is typically associated with a lack of precipitation combined with above average temperatures,

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increased net radiation, increased wind speeds, and rapid depletion of soil moisture (Hunt et al., 2014; Otkin et al., 2013, 2016; Ford and Labosier, 2017; Basara et al., 2019; Christian et al., 2019). In late May and early June, rapid drought intensification began across southwestern Russia (Christian et al., 2020). By early July, the flash drought led to highly desiccated land surface conditions over the region, prior to the onset of the August heat wave (displayed in Figure 6 of Christian et al., 2020). Two primary meteorological components have been connected to the development of the flash drought and heat wave over western Russia in 2010. First, a quasi-stationary upper-level ridge was centered over western Russia during July and August (Barrioperdro et al., 2011; Grumm and R H, 2011; Christian et al., 2020). This led to sustained periods with suppression of precipitation and persistent high atmospheric demand. Second, the continuation of anomalously high surface temperatures was supported by land-atmosphere coupling via heat storage in nocturnal residual layers that would re-enter the boundary layer during the day, thus perpetuating a positive feedback to sustain the heat wave for several days (Miralles et al., 2014).

Local impacts from the drought and heat wave were extraordinary. Thousands of people were displaced due to loss of property from wildfires (Bondur 2011) and severe air pollution from the fires significantly increased mortality during the late summer when the frequency and spatial extent of the wildfires were at their peak. In all, the resulting impacts associated with the heat wave and air quality problems led to a total of approximately 11,000 excess deaths (Shaposhnikov et al., 2014). The impacts to agricultural production were particularly severe, especially to wheat.

Wheat is the most important crop in Russia and accounts for over 60% of total grain production in the country (USDA-WASDE 2017), even though the total land area devoted to it represents a relatively small percentage of the country. Most wheat production is found in the North Caucasus, Southern, Volga, Central, and Western Siberia federal districts (Rosstat 2018). According to statistics from Rosstat, wheat in Russia has traditionally been split between winter wheat and spring wheat, with winter wheat being grown primarily in the Central, North Caucasus, Southern, and Volga federal districts and spring wheat in the Volga, Urals and Siberian federal districts. Weather along with subseasonal to seasonal variability play a major role in production in Russia, with highly variable yields across the country being common (Gotz et al., 2016). However, the 2010 growing season was unique in that both winter and spring wheat crops were severely impacted by drought. Rojas et al. (2018) further adds that the summer of 2010 was the only time in a 30-year period (1986–2015) that both winter and spring wheat in the Russian Federation were simultaneously affected by any level of drought, much less extreme drought.

The timing and characteristics of the drought and heat wave were especially damaging for both wheat crops. For spring wheat, an air temperature ranging from 20 to 25 °C is considered optimum for growth and development (Acevedo et al., 2002; Hakim et al., 2012). During the summer of 2010, temperatures were routinely 32–35 °C and occasionally approached 40 °C during the peak of the heat wave in August. The timing and location of the drought in 2010 was detrimental to food security for reasons beyond the drought conditions. The primary reason is that Russia had become a prime exporter of wheat in the years prior to the drought (Svanidze and Gotz 2019) due to improved management practices, technology, and re-cultivation of land that had gone idle after the Soviet Union had dissolved (Swinnen et al., 2017; Svandize and Gotz, 2019).

While Russia being a net exporter of wheat during a historically severe drought was not a food security issue by itself, its importance to the global market sparked panic in the wheat markets during the summer of 2010. For example, according to data from the USDA, wheat prices on the global market rose 20% in consecutive months (July and August) for the only time in a 25-year period from 1996 to 2020. Furthermore, the countries that were the largest customers and most reliant on Russian wheat exports compounded the issue. Thus, when Russia banned the export of wheat on August 5, 2010, contract prices for wheat in countries such as Egypt, Tunisia, and Turkey immediately soared. It is the combination of the rapid increase in contract prices for wheat and its byproducts combined with persistently high prices that has been considered a possible factor in the unrest of the Arab Spring in 2011 (Welton 2011).

In this paper, we build upon existing research by quantifying the spatial evolution of drought conditions during the summer of 2010 in Russia and its effects on agriculture that led to a food security crisis in the months that followed. In particular, we demonstrate that the timing of the onset, the locations affected, and the rapid intensification of the flash drought were critical to the rapid increase of wheat prices, which may have been a factor for cascading socioeconomic impacts in other areas of the globe.

2. Study area

The study area is over western Russia, sometimes referred to as European Russia. For analysis of the evolution of the flash drought, we broke the area into five regions with latitude and longitude bounds shown in Table 1 and Fig. 1. The impacts to wheat yield and production are reported for oblasts, many of which are contained within the regional boundaries. Winter and spring wheat yield and production data from 1996 to 2018 were analyzed for 29 oblasts over western Russia. The top producing winter wheat oblasts (yellow, Fig. 1) are found near the border with Ukraine and close to the Black Sea and is the dominant crop in Regions 2 and 4. The top producing spring wheat oblasts (brown, Fig. 1) are found further to the north and east where conditions have traditionally been more favorable for spring wheat production. This is the dominant crop in Regions 1, 3, and 5. The Saratov oblast, which falls between the two areas, is a top producer of both. It should be noted, however, that winter wheat acreage has been increasing at the expense of spring wheat acreage over the past decade across most of western Russia, owing partly to milder winters and partly to agricultural adaptations by area farmers (Rosstat, USDA-FAS).

3. Methods

The NASA Land Information Systems (LIS) is a modeling and data assimilation framework for terrestrial earth modeling that allows for integration of modeled and observational data to produce optimal states of land surface variables (e.g., soil moisture) and water and energy fluxes (Kumar et al., 2006; Peters-Lidard et al., 2007). In this paper, we show results of a soil moisture index (SMI, Hunt et al., 2009) from LIS to show the effect of the flash drought on root-zone soil moisture and as a proxy for water stress on the wheat crop. The SMI was generated from the root-zone soil moisture product from the Noah-Multiparameterization (Noah-MP; Niu et al., 2011) land surface model, which was run in LIS at 25-km resolution and driven with forcing from the NCEP Global Data Assimilation System (GDAS; Derber et al., 1991), over a 20-year period from 2000 to 2019. The index is scaled from −5.0 to 5.0, where −5.0 (5.0) represents the minimum (maximum) water content for a 25-km grid box for a particular period of time, which in this analysis is one-week intervals between mid-April and early

Table 1
Latitude and longitude bounds of the defined regions for analysis and the oblasts contained in the region. Asterisks indicate a top producing oblast of either winter or spring wheat.

Region	Longitude	Latitude	Oblasts
1	50.5–54.9 E	52.0–55.0 N	Bashkir*, Orenburg*
2	40.5–45.5 E	49.1–52.5 N	Saratov*, Volgograd*
3	42.0–45.5 E	52.5–56.2 N	Samara*, Tatarstan*, Ulyanovsk*
4	35.5–40.5 E	50.5–53.5 N	Lipetsk*, Tambov*, Voronezh*
5	35.5–40.5 E	53.5–56.4 N	Moscow, Ryazan, Vladimir

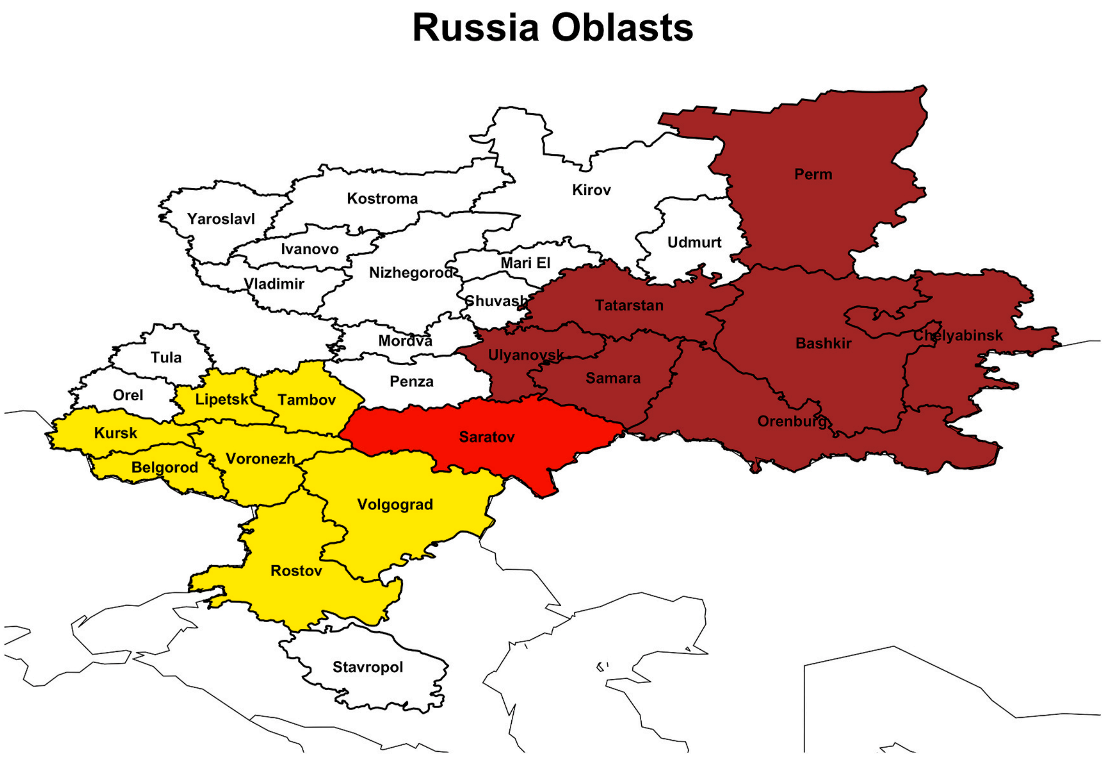

Fig. 1. Russian oblasts used for analysis. Oblasts in yellow are the top producers for winter wheat. Oblasts in brown are the top producers for spring wheat and Saratov (red) is a top producer of both. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

September.

The Evaporative Stress Index (ESI; Anderson et al., 2007a, 2011; 2013) represents standardized anomalies in the ratio of actual evapotranspiration (ET) to potential evapotranspiration (PET), which are generated with the thermal remote sensing-based Atmosphere-Land Exchange Inverse (ALEXI) surface energy balance model (Anderson et al., 2007b). Negative ESI indicates that normalized ET is lower than normal over a given compositing window (typically 2, 4, 8 or 12 weeks, advancing at 7-day intervals), indicating depleted soil moisture and vegetative stress. ESI values of −2.0 (2.0) represents the bottom (top) 2.5 percent of the distribution; thus, an ESI below −2.0 are typically associated with severe drought conditions. The ESI is computed routinely over the globe at 5-km resolution using day-night temperature differences from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Hain and Anderson, 2017). In this paper we show results from the 4-week ESI at 5-km resolution over the same domain as the LIS simulation. Previous studies have identified strong correlations between ESI and yield anomalies in the US (Otkin et al., 2016; Mladenova et al., 2017; Yang et al., 2018, Yang et al., 2021), Brazil (Anderson et al., 2016a) and Czech Republic (Anderson et al., 2016b).

Yield, acreage, and total production data for winter and spring wheat at the oblast level of Russia over a period from 1996 to 2018 were obtained from the United States Department of Agriculture Foreign Agricultural Service (USDA-FAS). Linear regression was used to determine the percentage deviation from the trend line (i.e., above or below) winter and spring wheat at the oblast level over the entire period of record from 1996 to 2018.

Global monthly wheat stock data were obtained from World Agricultural Supply and Demand Estimate reports that are published by the World Agricultural Outlook Board of the USDA. Global monthly wheat price data were obtained from an archive of USDA data that is hosted by IndexMundi. Daily global wheat prices from 2010 are not available so we used an archive of U.S. wheat contract futures from investing.com.

4. Results

4.1. *The flash drought*

The analysis of the spatial evolution of the 2010 flash drought over western Russia is broken into five regions (refer to Table 1) using both the SMI and ESI. Snapshots of the SMI (Fig. 2a) and ESI (Fig. 2b) are shown for six dates during the 2010 growing season. Fig. 3a and b shows the median SMI and 1-month ESI respectively at a weekly timestep during the 2010 growing season. Early in the season, the SMI indicated relatively moist soils over western Russia, with the exception of some dryness in Region 5. A dry and warm month of April led to significant declines in the SMI but less so with the ESI, especially over the heterogeneous landscapes of Regions 4 and 5. Refer to Schepaschenko et al. (2011) for a detailed land cover map of Russia.

Precipitation returned to the region for a brief period in late May, leading to moist soils again for a large part of western Russia and Ukraine. Unfortunately, this was not enough to significantly recharge soils over the Regions 1–3 where wheat dominates the landscape. After the first part of June, precipitation ceased and remained almost entirely absent for the next two months over most of western Russia (Christian et al., 2020). By early August, the SMI had dropped to −5 over most of western Russia and the ESI had dropped below −2 in most locations as well, indicative of the severity of the drought.

4.1.1. *Region 1*

Figs. 2a and 3a show that root zone soil moisture became depleted extremely quickly between 10 April and 15 May as the median SMI for the region dropped from 0.9 to −4.7 (Supplemental Table 1, ST1a). After brief improvement during the second half of May, the median SMI again fell quickly to −5 by the end of June where it remained for the rest of the growing season. For a sense of perspective, the median root zone soil moisture was at its 20-year minimum for eleven consecutive weeks over a region covering nearly 100,000 km^2. The 1-month ESI also began the growing season in positive territory with a median value of 1.15.

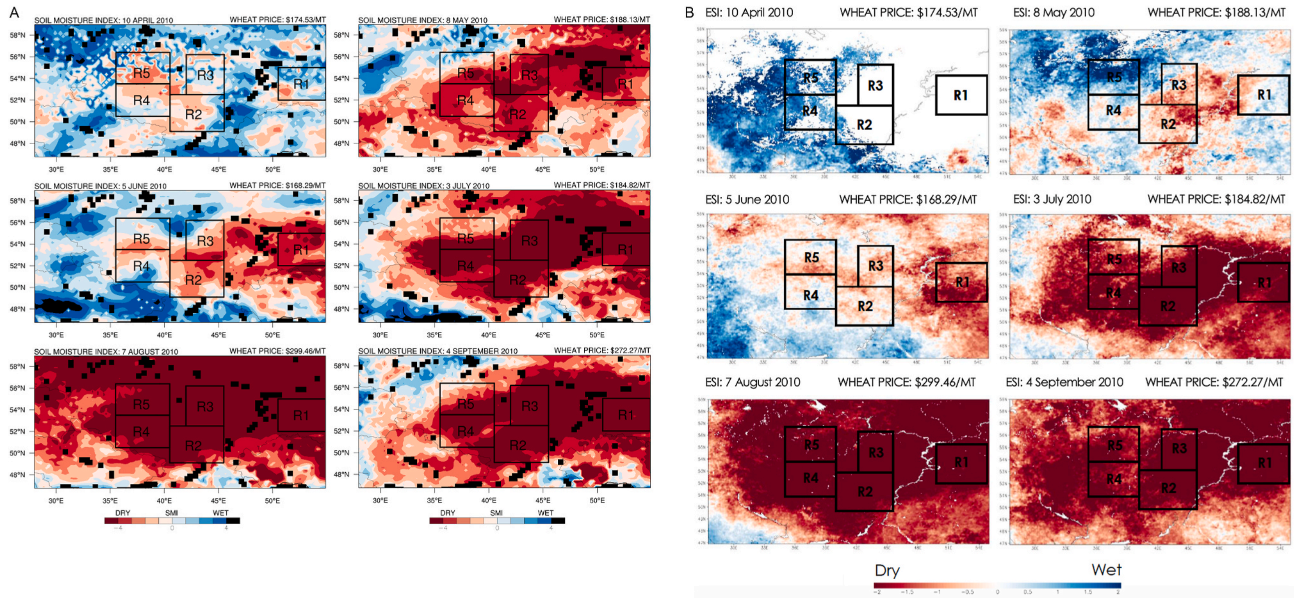

Fig. 2. a. From top left to bottom right, Soil Moisture Index (SMI) over western Russia for the following weeks in 2010: 10 April, 8 May, 5 June, 3 July, 7 August, and 4 September. The maximum wheat price ($/MT) for the five-day period ending 9 April, 7 May, 2 July, 6 August, and 3 September in 2010 is listed in the upper right. Regions 1 through 5 are denoted by R1-R5 respectively. Additional information is found in Table 1. b. From top left to bottom right, Evaporative Stress Index (ESI) for the following weeks in 2010: 10 April, 8 May, 5 June, 3 July, 7 August, and 4 September. The maximum wheat price ($/MT) for the five-day period ending 9 April, 7 May, 2 July, 6 August, and 3 September in 2010 is listed in the upper right. Regions 1 through 5 are denoted by R1-R5 respectively. Additional information is found in Table 1.

However, this was also short-lived as the ESI began declining, with rapid decreases occurring from the middle of May until the end of June (Fig. 2b). The median ESI continued to decline through the remainder of the summer, reaching its most negative value of −2.66 on 4 September. The areal expansion of the ESI less than −2 was also rapid, going from less than 0.5% of Region 1 on 15 May to 95.0% on the 17 July (Supplemental Table 2, ST1b). The area in Region 1 with an ESI less than −2 remained over 92% the rest of the season, with a peak of 96.5 percent on 28 August.

4.1.2. Region 2

Conditions were similar to Region 1 in the growing season of 2010, albeit slightly less extreme. The initial decline in soil moisture in April and early May was a bit less sharp than further to the east in Region 1 and the improvement in the last part of May was more substantial (Fig. 2a–b). But as in Region 1, this reprieve was short-lived as there were substantial declines in the median SMI, going from a season high of 0.6 on 29 May to −5 on 26 June (ST1a). The median SMI remained at or near −5 over Region 2 for the remainder of the growing season. The median ESI declined quickly early in the season from 0.22 on 24 April to −1.02 three weeks later. This was followed by a short period of improvement that coincided with the moistening of soils. But this improvement was short lived as the median ESI dropped from −0.22 (near average) to −2.31 (extremely dry) over the course of just four weeks. The median ESI remained below −2 the remainder of the season with a minimum of −2.44 being reached on 7 August. A strong majority of grid points in Region 2 were below −2 on a given day after 26 June, with a peak of 81.2% on 7 August (ST1b).

4.1.3. Region 3

Conditions may have been the worst over Region 3, covering much of the oblasts of Saratov and Volgograd. At no point in the season was the median SMI >0 and the lowest ESI values were found in this region (Fig. 2a–b). As over Regions 1–2, the median SMI dropped quickly in April and the first half of May, reaching −5 by 15 May. But as in Region 2 there was a marked improvement in the SMI over the last two weeks of May to reach −0.6 on 29 May (ST1a). This improvement was short-lived as the median SMI rapidly dropped to −5 by the end of June, where it remained through early September. The median ESI was on positive in late April but dropped quickly to −1.23 by the end of May. After a brief improvement in early June in response to improved soil moisture, the median ESI dropped rapidly below −2 by early July. The median ESI continued to drop through July, reaching an incredible minimum of −2.84 on 31 July, with over 98% of Region 3 having an ESI < −2 (ST1b). The median ESI remained < −2.5 through at least early September, with 90% or more of the grid points having an ESI below −2.

4.1.4. Region 4

Further to the west over the Lipetsk, Tambov and Voronezh oblasts, the median SMI was already negative at the beginning of the season (Fig. 2a) and dropped to −3.1 by 8 May. As with the other regions, the second half of May saw improvement and in Region 4, it was rather substantial with the median SMI remaining above 0 from 22 May to 5 June (ST1a). This was followed by a rapid decline in soil moisture during the month of June, with the SMI going from 0.9 on 5 June to −4.2 just three weeks later. The remainder of the season was very dry with the median SMI mostly staying below −4 and reaching −5 for two weeks in the month of August. The median ESI began the season strongly positive indicating healthy vegetation (Fig. 2b). After the onset of the dry spell in late April and early May, the ESI dropped below 0 for a few weeks and then rose back to marginally positive values in early June. This reprieve was short-lived though. During the period from 12 June to 3 July, the median ESI dropped from 0.12 to −2.17 (ST1b). The median ESI remained below −2 throughout August, hitting a minimum of −2.56 on 7 August.

4.1.5. Region 5

Of the five regions used for analysis, Region 5 had the lowest median SMI on 10 April. The SMI remained negative through late May (Fig. 2a). But unlike the other four regions which cascaded rapidly into drought during the first half of June, Region 5 stayed relatively moist with SMI values close to 2 on 12 and 19 June. But the reprieve ended thereafter with a rapid decline from 1.7 on 19 June to −4.4 on 17 July and reaching −5 on 31 July (ST1a), where it remained for two more weeks.

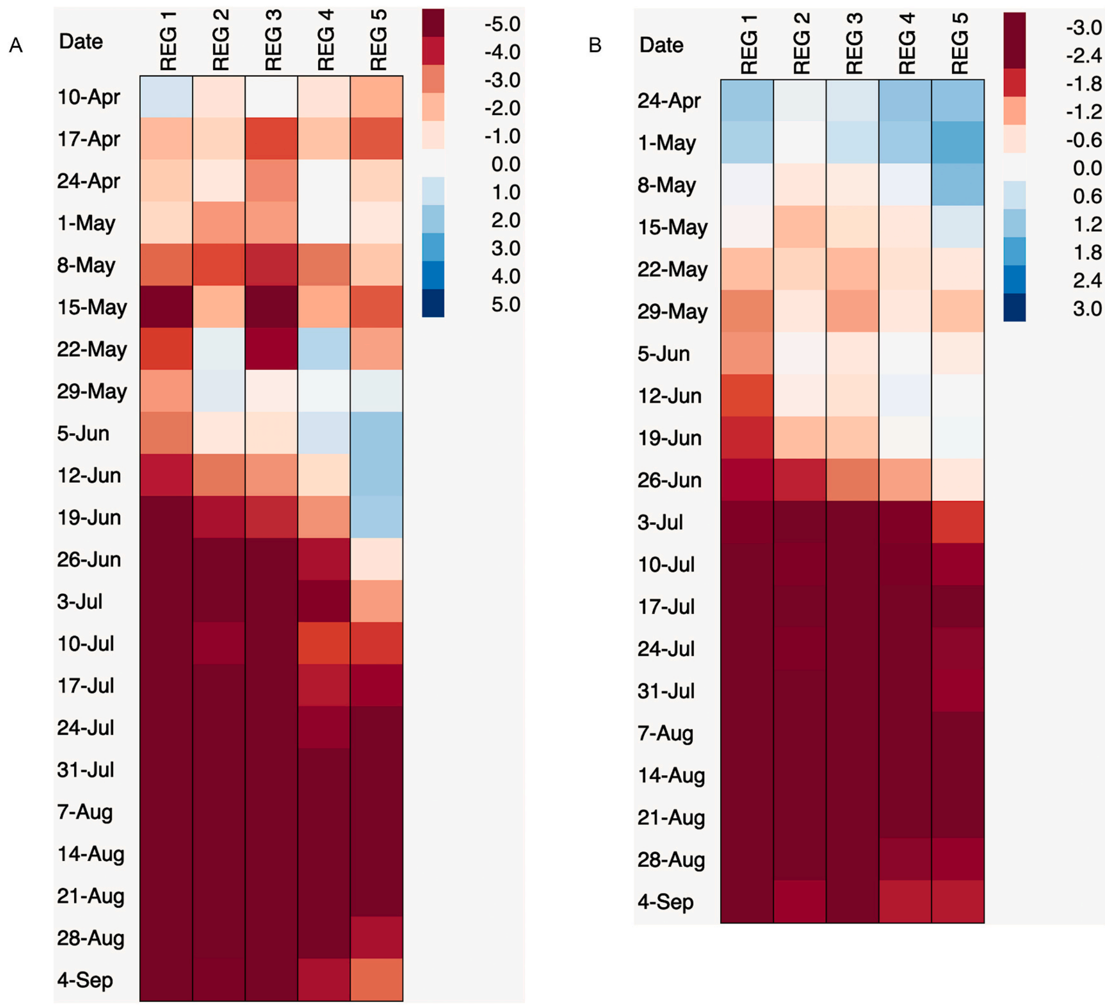

Fig. 3. a. A heatmap of the 1-week SMI ending on the date in 2010 shown in column 1. Legend is contained in the upper right corner. b. A heatmap of the 4-week ESI ending on the date in 2010 shown in column 1. Legend is contained in the upper right corner.

Also unlike the other four regions, there was a slight improvement in the median SMI toward the end of the season. As in Region 4, the median ESI was strongly positive for the first few weeks (Fig. 3b), followed by a modest decline in May. With the increase in the median SMI in June came improvement in the median ESI and by 19 June was slightly positive. The median ESI then fell rapidly below −2 where it remained through the end of August, reaching a comparably less extreme minimum of −2.29 on 17 July and −2.28 on 7 August (ST1b).

4.2. *Agricultural impacts*

The flash drought and heat wave that affected much of western Russia in the summer of 2010 had devastating impacts on both the winter and spring wheat crop and the timing of the onset of the flash drought in early June could not have been worse. According to the crop calendar from the USDA-FAS, winter wheat typically enters its flowering period in the most productive oblasts of southwestern Russia around the first week of June. Thus, the most critical period for winter wheat yield in places like the Volgograd oblast was marked by an absence of precipitation and a depleted soil moisture profile. In Fig. 2a–b and 3a-b, this period of time fell between the images from 5 June and 3 July respectively. A majority of the top producing oblasts for winter wheat (denoted in Fig. 4 by an asterisk) were more than 40% below trend. The most extreme yield departures of more than 50% below trend were found over the oblasts of Saratov, Tambov, and Voronezh. Conditions were somewhat less extreme in the far southern portion of Russia where the top winter wheat producing oblast Rostov was 10% below trend and Stavropol was almost at trend.

Aided by much above average temperatures, the flash drought was in its most rapid intensification phase around the same time flowering began on the spring wheat crop in western Russia in 2010. The critical flowering stage likely occurred mostly between late June and early August in Fig. 3a–b. Thus, most locations in Regions 1, 3, and 5 where spring wheat is the dominant crop likely had depleted soil moisture and severe drought stress at the start of flowering. The flash drought continued to intensify and expand during flowering and the result was almost complete devastation to the spring wheat crop. Fig. 5 shows that all oblasts in western Russia were more than 10% below trend and most were at least 50% below trend. Perhaps most critically, the area of western Russia with most rapid intensification and extreme conditions (as shown by the ESI in Fig. 2b) occurred over the most productive oblasts for spring wheat, which meant that oblasts such as Saratov and Tatarstan had spring wheat yields that were more than 80% below trend.

The total combined production of winter and spring wheat in Russia in 2010 was 41.5 million metric tons (MT), a drop of over 20 million MT compared to both 2008 and 2009. The impact to production was most acute for the top producing oblasts as well. Table 2 shows that most oblasts in the prime winter wheat region (refer to Fig. 1) had at least a 50% reduction in production when compared to the average of 2008–2009. The most significant reductions were in Belgorod and Voronezh, with reductions of 75% and 80% respectively. The impacts to spring wheat were even more severe with most oblasts having

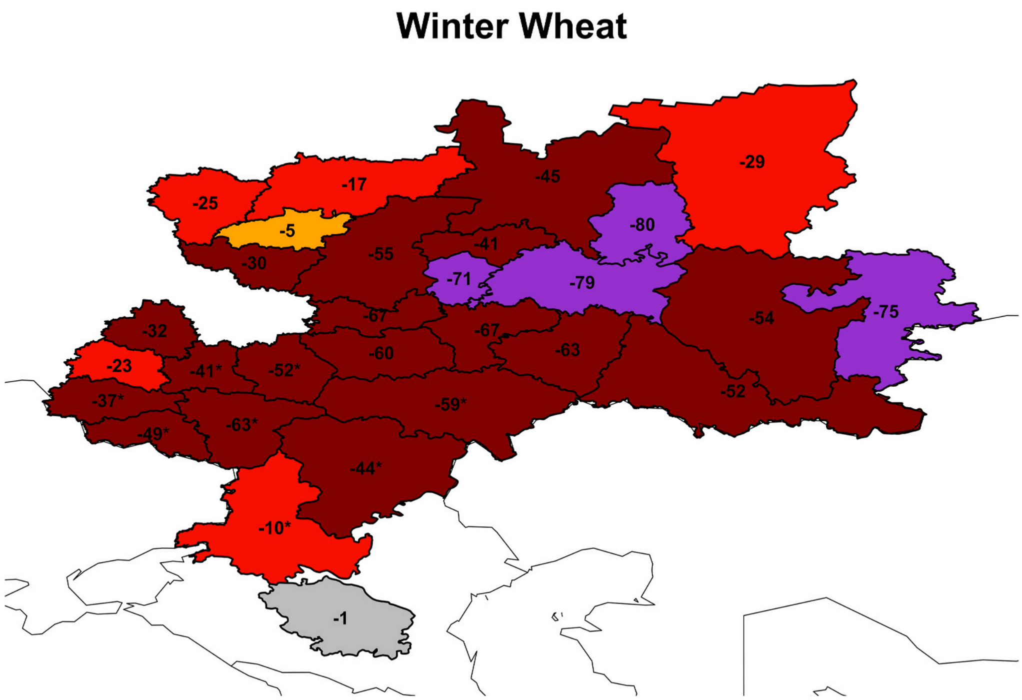

Fig. 4. Percentage points below trend for winter wheat as determined by data from USDA FAS. The top producing districts are denoted by an asterisk. Color legend as follows. Gray (0 to −2), orange (−3 to −10), red (−10 to −30), dark red (−30 to −70), and purple (<−70). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

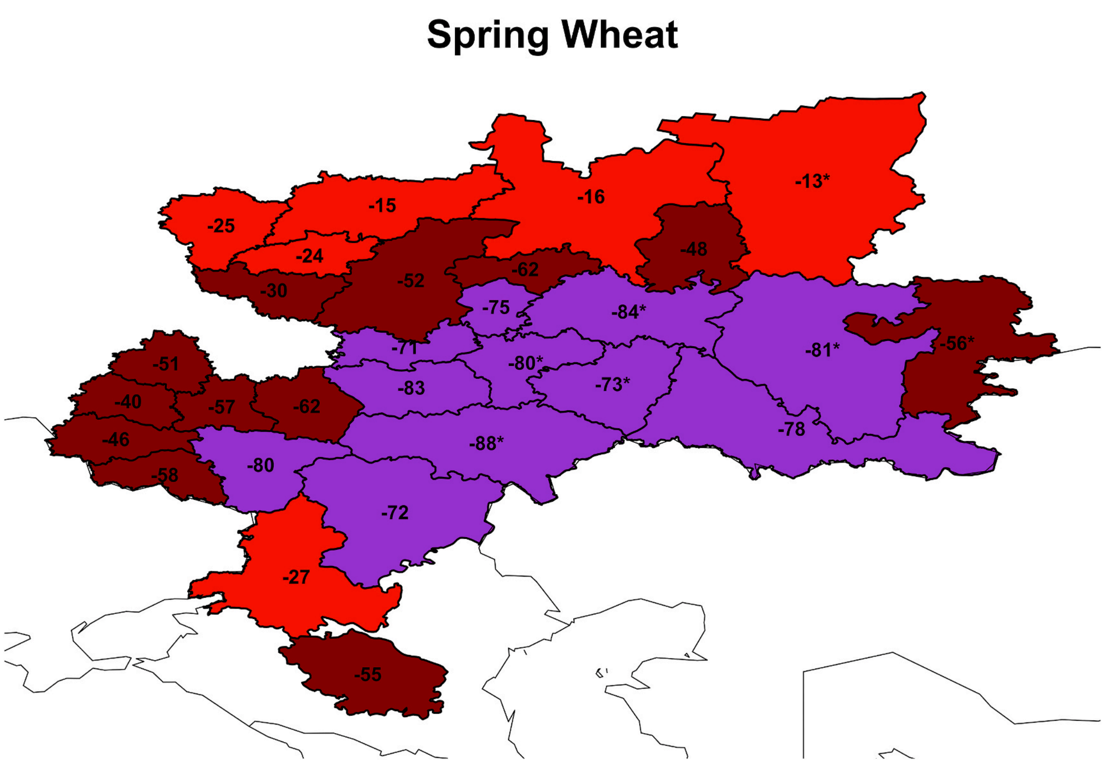

Fig. 5. Percentage points below trend for spring wheat as determined by data from USDA FAS. The top producing districts are denoted by an asterisk. Color legend as follows. Gray (0 to −2), orange (−3 to −10), red (−10 to −30), dark red (−30 to −70), and purple (<−70). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

reductions over 75% compared to 2008–2009 and as high as 92% in Saratov.

The development and intensification of the flash drought not only occurred at the worst possible time for both of these crops in 2010, it also occurred over the most productive wheat producing region of Russia. Had this drought developed later in the season or had it been offset to the north or south, the impacts to production likely would have been less severe. The impacts of this flash drought unfortunately were

Table 2
The percentage reduction of winter wheat production (left) and spring wheat production (right) compared to the average production of the 2008–2009 seasons.

Winter Wheat		Spring Wheat	
Oblast	% Reduction	Oblast	%Reduction
Belgorod	75	Bashkir	85
Kursk	36	Chelyabinsk	55
Lipetsk	43	Orenburg	83
Rostov	10	Perm	31
Saratov	59	Samara	78
Tambov	64	Saratov	92
Volgograd	65	Tatarstan	84
Voronezh	80	Ulyanovsk	76

not confined to Russia and the next section gives a broad overview of the international impacts to food security that occurred because of this extreme event.

4.3. Impacts to food security

By the beginning of August, it was apparent that the flash drought and its associated heat wave were going to lead to significant reduction in both yields (MT ha^{-1}) and total production (MT) of wheat in western Russia. The USDA World Agriculture Supply and Demand Estimate report in August 2010 noted that expected Russian wheat production would be reduced 8 million MT with additional reductions of 2.5 million MT in neighboring Kazakhstan and Ukraine due to similar conditions as in western Russia. This reduction also had a significant impact on the global wheat stocks. Between the months of June and August, global demand for wheat remained constant but the supply dropped from 861.4 million MT to 839.8 million MT (USDA-WASDE, 2010). Thus, global wheat stocks dropped from 193.9 million MT to 174.7 million MT between June and August (Supplemental Table 3). This sharp drop in supply also corresponded with a rapid increase in prices.

For example, at the onset of the flash drought in early June, wheat prices were around $170/MT (U.S. dollars). As drought conditions worsened, the price of wheat increased, slowly at first and then rapidly later in July. As shown in Figs. 2 and 3, by early August wheat prices had climbed to almost $300/MT (Bora et al., 2010). While wheat prices were higher in early 2008 and were higher again in 2012, the months of July and August of 2010 are the only occurrence of consecutive months with a 20 percent increase in the global wheat price since at least the mid-1990's. The steep rise in global wheat prices in July and early August of 2010 was exacerbated by Russian grain speculators that intentionally kept grain off the market because of expectations of an export ban. This anticipation of an export ban by the Russian government came to fruition on 5 August and was a fulfillment of its Food Security Doctrine that was adopted by President Medvedev in January 2010 (Welton 2011). The Food Security Doctrine established minimum self-sufficiency standards for Russia, which included being able to produce 95 percent of its grain (including wheat) and potatoes (Lunze et al., 2015). Thus, the export ban was implemented to ensure greater self-sufficiency. Most Russians did not see a financial benefit from the export ban, however, and the poorest people in the country were particularly affected by the significant increase in prices, as the official price for a subsistence basket rose upwards of 30% in just a few months (Welton 2011).

In the decade following the dissolution of the Soviet Union, Russian agricultural policy focused on dramatically increasing grain production as a way of making Russia a key grain exporter. Economic nationalism was the key driver of this effort, using protectionism and state investment to boost production prior to the 2010 drought (Wegren 2010). By the late 2000s, therefore, Russia was a net exporter of wheat, and in the years leading up to 2010, countries such as Egypt were significantly dependent on wheat exports from Russia, as well as China and a few other global wheat suppliers. In 2010, the top wheat importers were Egypt and Algeria followed by Brazil, Japan, Korea, Morocco, and the U.S. (Taylor and Koo, 2011). Thus, when the Russian government banned the export of wheat in early August 2010, it contributed to an unfortunate chain reaction. The Russian wheat ban went into effect shortly before a "once-in-a-century winter drought" in China (Barriopedro et al., 2012), as well as downturns in other major wheat-producing regions. For example, wet and cool conditions affected the amount of wheat planted in parts of Canada (USDA-FAS 2010) and significant drought adversely affected wheat yield in western Australia (Rural Business Development Corporation, 2014).

The reduced production in major wheat growing places like Canada and Western Australia further strained the wheat supply. As a result of wheat supply shortages, global wheat prices doubled between June 2010 to February 2011, from $149/MT to $318/MT (Supplemental Table 4; Werrell et al., 2015). During this time period, high wheat prices prompted the Mozambique government to raise bread prices by 30%, which led to broader social unrest, including food riots with a small number of fatalities (Berazneva and Lee 2013). The price of wheat flour increased by 10 percent or more during the July–October 2010 period in Kyrgyzstan, Mauritania, Afghanistan, Sudan, Armenia, Azerbaijan, Pakistan, and Bolivia (World Bank Food Price Watch, 2010). Furthermore, the high wheat prices were a factor in a 26 percent increase in the Food Price Index from the Food and Agriculture Organization (FAO) between June and November (Foley 2010).

Wheat is a very important grain in Egypt and the broader Middle East and North Africa, as it is the base of bread, which is a cultural staple and a large source of calories for poorer populations. As wheat prices rose sharply, bread prices rose 300% by early 2011 across a number of areas of Egypt, straining the capacity of the country's bread subsidy regime, and leading to bread riots in rural areas across the country that coincided with civil unrest in the country's cities – thus broadening the appeal of the anti-Mubarak movement outside urban areas (Femia et al., 2014). Welton (2011) reports that this was particularly problematic in Pakistan as a large increase in prices was coupled with the reduction in food protection prices by the government, thereby increasing the poverty rate. It is the combination of the rapid increase in the contract prices for wheat and its byproducts, combined with sustained high prices, that is thought to be a non-trivial factor in expanding the popular appeal of unrest during the Arab Spring (Jones 2012), particularly to rural communities that were highly dependent on bread and vulnerable to price volatility (Lubin 2011). This is not to imply that high wheat prices alone were directly responsible for the Arab Spring; rather they were a complicating factor in a region plagued with persistent poverty and inequality (Ianchovichina et al., 2015; Klasen 2018).

The event was also a reminder that the balance between agricultural 'food security' and global trade in Russia is a tenuous one (Wegren and Elvstad 2018). Russia's long and painful history of famine still weighs heavily on the population. In 2015, Russia's President Putin ordered the destruction of banned western food imports, which sparked a rare public backlash because it revived memories of food shortages during the Soviet era (Baczynska 2015). While the Russian state was able to intervene in 2010 to subsidize farmers and stabilize the grain supply through the use of reserves, it is uncertain whether the regime could mollify a population with a fear of shortages through multiple seasons. This uncertainty could be exacerbated by extreme events made more probable by climate change. Finally, the cascading socioeconomic impacts that occurred in 2010–2011 might offer us a warning and possibly some clues about the stakes of climate change in increasingly tenuous geopolitical times.

5. Discussion and closing thoughts

The occurrence of extreme drought and heat over a large agricultural region, such as western Russia, is by definition an unusual meteorological event. The timing of the development of the flash drought and the locations affected by the flash drought were very important to the food security crisis. The onset of the flash drought was such that both spring wheat and winter wheat crops in western Russia had very low available soil moisture and unusually warm temperatures during the critical flowering stage. Previous research (Miralles et al., 2014; Schumacher et al., 2019; Christian et al., 2020) has demonstrated the desiccated agricultural landscape also exacerbated the magnitude and the persistence of the heat wave in late July and August 2010, leading to additional yield loss. Furthermore, this flash drought and heat wave affected the most productive places for winter and spring wheat in Russia, thereby compounding the production losses.

If the flash drought had begun six weeks later, the impact to winter wheat likely would have been minimized and the impact to spring wheat would have been less substantial as moisture would have been more adequate going into flowering. Likewise, if the epicenter of the flash drought had been offset to the north by 500 km, the impacts to agriculture would have been lower because the highly productive oblasts for both winter and spring wheat would have either been outside the drought or on the periphery. As it was, the flash drought and heat wave affected the most productive wheat areas at the worst possible time. This was the most extreme regional drought in decades (Welton, 2011) and the relative novelty of the extreme flash drought had unusually severe societal consequences. At least two impacts can be directly attributed to the 2010 flash drought over western Russia (Christian et al., 2020). The first was the significant loss of life (i.e., over 11,000 excess deaths) from the heat wave and air quality impacts from the forest fires that followed the flash drought. The second was a reduction of over 20 million MT of wheat (a reduction of 34%) compared to the previous two years produced by Russia.

The spooked reaction in the markets to the anticipation of a significant reduction of wheat and the expectation of an export ban by the Russian government was perhaps the first food security domino to fall between the summer of 2010 and the spring of 2011. The next food security domino also had its connection to drought. An extreme drought that developed over eastern China (Barriopedro et al., 2012) also contributed significantly to the disorder and panic-buying in the grain markets in early 2011. As discussed in Werrell et al. (2015), the combination of these two droughts contributed to a doubling of the global price of wheat between June 2010 and February 2011. This made bread unaffordable in many countries, leading to increased poverty, bread riots and may have been a contributing factor to regime change in countries such as Egypt and Tunisia during the Arab Spring.

Extreme droughts are part of natural variability but the exceptional nature of the flash drought in Russia in 2010 may be a warning sign that rapidly intensifying flash droughts may become more common due to climate change (Rahmstorf and Coumou, 2012). Furthermore, flash droughts may be more likely to occur in some of the globe's most productive agricultural regions in the same calendar year (Anderson et al., 2017), which could generate cascading impacts that would affect global good security. For example, a repeat of the 1936 drought in the central U.S. (Cook et al., 2008, 2009; Peters and Burruss, 2020; Hunt et al., 2020; Bolles et al., 2021) coupled with simultaneous production losses of maize and soybean in Brazil (Anderson et al., 2017) could potentially have severe consequences for global food security. As was the case with the Russia flash drought in 2010, if it led to panic in the global markets, a hypothetical argument could be made that numerous countries would independently enact export bans to protect their own supply. This in turn likely would lead to drastic price increases for maize and soybean and significant disruption to the supply chain.

Authorship

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Declaration of competing interest

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Appendix A. Supplementary data

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