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Increasing risks of crop failure and water scarcity in global breadbaskets by 2030

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E-mail: mcaparas@woodwellclimate.org**Keywords:** crop yields, crop failure, climate risk, AgMIP, agricultural breadbaskets, water scarcitySupplementary material for this article is available [online](#)

Abstract

As the greatest water user in the world, the agricultural sector is vulnerable to changes in climate and water resource availability. Understanding the impact of these changes on crop yield is critical in order to achieve and maintain global food security. We analyze output from an ensemble of Agricultural Model Intercomparison and Improvement Project models to project the probability of rice, soybean, maize, and wheat yield failures across global and national breadbaskets through mid-century. The probability of crop yield failures is projected to be as much as 4.5 times higher by 2030 and up to 25 times higher by 2050 across global breadbaskets. Crop failures are projected to be more likely when effects of CO₂ fertilization are ignored. We utilize the open-source Aqueduct Water Risk Atlas to create a Water Scarcity Index composed of ten hydrological variables. The index reveals high water scarcity across crop breadbaskets in India, China, and the United States. If the ability to irrigate breadbaskets was eliminated due to water scarcity, the likelihood of crop failures would increase. Shifts in breadbaskets may cross national borders as crop yields will increase in Canada and decrease in the US as a response to a changing climate. Our analysis highlights top producing agricultural regions that have historically provided the global food system with large quantities of one or more major crops, but will face challenges in continuing to do so due to climate change and growing water scarcity.

1. Introduction

Global demand for food and water is rising due to changing consumption patterns, rising global population, and continued development particularly in the agricultural sector (Vörösmarty *et al* 2000, Erzin and Hoekstra 2014). Though global food production has increased, food security has yet to be achieved as global hunger has been on the rise since 2014 with one in every nine people experiencing undernourishment as of 2017 (Thenkabail *et al* 2012, Wheeler and von Braun 2013, Molotoks *et al* 2021). The two main strategies in increasing global food production are cropland intensification and expansion. To meet global food demand without expanding cultivated areas, the agricultural sector will likely need to expand irrigated croplands where resources are available (Rosa *et al* 2020). However, 70% of all global

freshwater withdrawals are already used for irrigation (McDaniel *et al* 2017). Global water scarcity is increasing and balancing the relationship between agricultural production and water usage is a delicate task. Growing enough crops without increasing water use, especially within a changing climate, is an urgent challenge for society.

Two-thirds of food calories worldwide is derived from four staple crops—wheat, maize, rice, and soybean (Kim *et al* 2019). Global production of these staple crops is highly concentrated in regions known as breadbaskets. At least 72% global production of each of the four staple crops occurs in five countries (supplementary table 1 (available online at stacks.iop.org/ERL/16/104013/mmedia)). Given the outsized role breadbaskets play in food production, understanding their stability under anticipated warming is critical for global food security.

Large-scale crop yield failures, i.e. failures within a breadbasket or across multiple breadbaskets, threaten food security through losses in yield and rises in food prices (Tigchelaar *et al* 2018). Such crop failures have been associated with extreme weather. Li *et al* (2019) found that in the US, excessive rain-fall can reduce maize yield up to 34% relative to the expected long-term trends. As extreme weather events increase in intensity and frequency with climate change, breadbasket failures are expected to become more likely. Here we define a breadbasket failure as at least 10% decline in yield. Previous studies have explored breadbasket failures and production shocks through the lens of synchronized and simultaneous events using regression models, copulas, and other statistical methods on observational crop yield data (Tigchelaar *et al* 2018, Gaupp *et al* 2019, Mehrabi and Ramankutty 2019). In this study, we calculate the likelihood of breadbasket failures in response to changes in temperature, precipitation, and atmospheric CO₂ concentrations on crop yields projected by an ensemble of global gridded crop models (GGCMs) from the Agricultural Model Intercomparison and Improvement Project (AgMIP). The GGCMs in the ensemble are driven by global climate models (GCMs) and integrate several dynamic aspects of crop interaction with soil, atmosphere, and water. To our knowledge, this study is the first to utilize GGCMs to assess the impact of climate change on national and global breadbasket failures. The greatest increase in simultaneous breadbasket failure is expected to occur between 0.85 °C and 1.5 °C warming above pre-industrial global mean temperature (Gaupp *et al* 2019). We reached 1 °C warming in the last decade (World Meteorological Organization 2021). Next decade, we are expected to reach 1.5 °C (Millar *et al* 2017). This urgency motivates the short time horizon of this study, from the present through mid-century. Understanding the likelihood of breadbasket failures in the upcoming decades will be crucial in addressing global food security in a changing climate.

There is potential to offset negative climate impacts on food security with the expansion of suitable, crop-growing climates to new regions. Throughout the 21st century, expansion of arable land is projected for high-latitude regions (Zhang and Cai 2011). Global northward expansion of suitable agricultural climate zones, defined by growing degree days, is projected to create 55%–89% more land feasible for growing crops in the boreal biome (King *et al* 2018). This may lead the way for the rise of new breadbaskets. However, the expansion of climate suitability for growing crops does not directly translate to increased agricultural productivity due to soil fertility, infrastructure, and alternative land use. We explore the possibility of shifting breadbaskets as a potential response to increasing breadbasket failure.

In this study, we address three key aspects of agricultural breadbaskets that will be impacted by climate change: crop yield failures, water scarcity, and changes in suitable crop-growing climates and area. To our knowledge, this is the first global study to tie all three aspects together on an urgent time horizon to 2050. We present projections of soybean, maize, wheat, and rice yield failures under different CO₂ and irrigation scenarios, an assessment of water scarcity across breadbaskets, and potential spatial shifts in breadbaskets due to the expansion of suitable climate. We discuss these three topics at a global level across all national breadbaskets of an individual crop and at a national level for the United States, India, and China.

2. Methods

Climate effects of precipitation, temperature, and CO₂ fertilization on maize, soybean, wheat, and rice yields in global and national breadbaskets are assessed by analyzing crop yield output obtained from AgMIP. Our global breadbasket is based on highly productive regions from the top five producing countries for each staple crop using 2013–2017 statistics from the Food and Agriculture Organization (FAO) (supplementary table 1). In addition to the global breadbasket, we examine three national breadbaskets in the US, India, and China. We calculate the probability of crop failure in global and national breadbaskets through 2050. We introduce the Water Scarcity Index (WSI), a relative global percentile ranking system based on ten hydrological indicators. We use this tool to identify water scarce regions within breadbaskets and assess the probability of crop failure in these regions. We calculate the probability of crop failure under two irrigation scenarios. Lastly, we identify spatial patterns of crop yield increases in regions neighboring national breadbaskets.

2.1. AgMIP

The AgMIP model ensemble focuses on the effects of atmospheric CO₂ concentrations, climate, water, and nutrients on long-term crop yield (Rosenzweig *et al* 2014). Crop yields from 1980 to 2099 are obtained from AgMIP output at 0.5° × 0.5° resolution. Only output from GGCMs that account for plant nitrogen limitation (EPIC, GEPIC, pDSSAT, and PEGASUS) is used, i.e. GGCMs that simulate potential yields are not considered. Two types of crop models are included in the ensemble: site-based (EPIC, GEPIC, and pDSSAT) and agro-ecosystem (PEGASUS). Information on the key characteristics and differences in GGCMs can be found in Rosenzweig *et al* (2014). All GGCMs are driven with consistent bias-corrected climate forcings under climate scenario RCP8.5 derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive. The GGCMs selected in this study are driven by five CMIP5 GCMs, with the exception of the

GEPIC run without CO₂ fertilization which is driven by one GCM. Maize, wheat, and soybean yields are simulated by four GGCMs, resulting in twenty members with CO₂ fertilization applied and sixteen without CO₂ fertilization. Rice yield is simulated by three GGCMs, resulting in fifteen members with CO₂ fertilization applied and eleven without CO₂ fertilization.

To understand the importance of water limitation, AgMIP considers two irrigation scenarios. One scenario assumes no irrigation. The second assumes full irrigation, or water is available to fully irrigate crops. We apply the full irrigation scenario to remote sensing derived global irrigated cropland areas and the no irrigation scenario everywhere else (Thenkabail *et al* 2012). This historical irrigation mask is applied throughout the simulated time period. It assumes only historically irrigated land will be irrigated in the future, and that irrigated land area will remain fixed. While it is unlikely that the amount of irrigated land will remain static in the future, the historical irrigation mask best reflects areas that already have the infrastructure in place for irrigation. We present the historical irrigation scenario as the default result and differences between historical irrigation and no irrigation scenarios to explore water scarcity risk.

One aspect of climate change that plays an important role in crop yield is the effect of CO₂ fertilization. Increased atmospheric CO₂ concentrations produce a negative feedback by enhancing crop productivity. As a result, it is hypothesized that CO₂ fertilization may partially offset negative climate impacts on crop yields (Rosenzweig *et al* 2014). Elliot *et al* (2014) projects lower climate-induced losses in global maize, soybean, wheat, and rice when CO₂ fertilization effects are accounted for versus when they are ignored. CO₂ fertilization may offset crop failures in models. However, more recent studies such as Wang *et al* (2020) show there is no observational evidence that CO₂ fertilization has had much effect on vegetation photosynthesis in recent decades and find a decline in the CO₂ fertilization effect on vegetation photosynthesis from 1982 to 2015. Additionally, the nutritional quality of crops produced will likely decrease with increased CO₂ (Uddling *et al* 2018, Beach *et al* 2019). This indicates possible limitations of CO₂ fertilization on crop loss mitigation. Because CO₂ fertilization is a large source of uncertainty of climate impacts on crop yields, we assess output from AgMIP simulations with and without CO₂ fertilization applied.

A caveat in the AgMIP ensemble is that agricultural technology, changes in infrastructure, crop cultivar development, and other adaptation strategies are not included in simulated yield. Through calibration to observed yields, the effects of pests and diseases may be implicitly included in some GGCMs.

The short time horizon of this study should limit this uncertainty to some degree.

2.2. Identifying breadbaskets

The spatial extent of a breadbasket is based on the highest crop producing area according to the US Department of Agriculture global production maps. Breadbasket masks are created using Earth-STAT 0.5° × 0.5° resolution global crop production datasets circa 2000 and applied to AgMIP output (Monfreda *et al* 2008). The extent of breadbasket regions is constant throughout the time period of this study.

Our global breadbasket leverages the high concentration of production for staple crops. At least 72% of global production for each crop is confined to five countries. For example, from 2013 to 2017, 88% of soybean production occurred in US, Brazil, Argentina, China, and India (supplementary table 1). The global soybean breadbasket is comprised of the top-producing regions of these five countries. Global breadbaskets for maize, rice and wheat are generated in an analogous manner relative to their top production countries (supplementary table 1).

In addition to the global breadbaskets, we also identify three multi-breadbasket nations: the US, China and India. The breadbaskets in these countries are a part of the respective global breadbasket. These three countries—critical to global food security—function as multi-breadbasket nations as they contain areas of high production for multiple staple crops.

2.3. Crop yield failure

Historical crop failures vary in magnitude by crop. For example, the 2012 drought in the US was a multi-billion-dollar agricultural disaster resulting in record food price spikes and crop yield losses (Schnoor 2012). Rippey (2015) reported a 26% reduction in maize yield and 9% reduction in soybean yield. Lesk *et al* (2016) show historical droughts and extreme heat events generally reduce national cereal production by 9%–10%. Here, a crop yield failure is defined by at least 10% decline in yield compared to average yield in the present period, 1998–2017.

Yield failures are projected for two future periods: 2021–2040 and 2041–2060. This work focuses on a more urgent timeline that is aligned within the 1.5 °C and 2 °C warming thresholds set by the 2015 Paris Agreement (UNFCCC 2015). Production is calculated from AgMIP yield output assuming the entire pixel area is cultivated. For each period, total production is summed across a national breadbasket or all five national breadbaskets for a global breadbasket. The relative change in total production is calculated for each breadbasket for each ensemble member. Relative change, as opposed to absolute value, is the best application of AgMIP output, as GGCMs differ in

their calibration procedures and inputs (Rosenzweig *et al* 2014).

Relative change is used to calculate the empirical cumulative density function (CDF) for each national breadbasket and collectively as a global breadbasket (see supplementary figure 1 for CDF plots of global wheat, rice, maize, and soybean breadbaskets). The CDF represents the probability in a given year during the time period crop yield will change by $x\%$ where x is any value between -100 to 100 , so while the results focus on a 10% failure, information about any level of breadbasket 'failure' is displayed using these CDFs. Each CDF is derived from all possible combinations of driving GCMs, GGCMs, and years within each 20-year period. That is, output from all ensemble members and all years are used to calculate the CDF. This results in a sample size for maize, soybean, and wheat of 400 for simulations with CO_2 fertilization; 320 without CO_2 fertilization. For rice, the sample size of 300 with CO_2 fertilization; 220 without CO_2 fertilization. Variations in sample size are due to available GGCM and GCM combinations. The range of model ensemble outputs by each GGCM and GCM combination for simulations without CO_2 fertilization can be found in supplementary figure 2.

2.4. Water scarcity

We identify areas of high water scarcity within breadbaskets using a WSI adapted from the open-source Aqueduct Water Risk Atlas (Hofste 2019). The WSI is a relative global percentile ranking system based on ten hydrological indicators: historical and future water stress, historical water depletion, future water supply, future water demand, future seasonal variability, historical interannual and seasonal variability of water supply, historical drought risk, and environmental flow limit from de Graaf *et al* (2019). Further discussion of each indicator can be found in the supplementary materials.

Each indicator is standardized by resampling to $\sim 10 \times 10$ km using nearest neighbor sampling and remapping to an interval of 0–10 of increasing adverse (more water scarce) risk. Each indicator is weighted according to an agricultural weighting scheme developed by Aqueduct based on corporate water experts (Hofste 2019, supplementary table 2). The standardized scores of all indicators of a single pixel are summed to give the pixel's total standardized score. All of the total standardized scores are then ranked by percentile. In the index, the overall score of a pixel is percentile rank, relative to the water scarcity of all other pixels around the world, with higher values representing more water scarce regions. This scoring system better quantifies the variation of water scarcity across locations. To provide context to the percentile ranking, the overall score is compared to the future water stress indicator. Previous studies refer to a water stress threshold of 0.40 to reflect severe water limitation (Vörösmarty *et al* 2000,

Hofste 2019). The 80th percentile is the median WSI score of all locations with a future water stress value between 0.39 and 0.41. Hereafter, high water scarcity refers to the 80th percentile (or greater) of the WSI.

We project the likelihood of crop failure within high water scarce regions of global breadbaskets. We utilize two types of water availability scenarios from AgMIP to compare projections of global and national breadbasket failures under conditions of historically sufficient irrigation versus under extreme water scarce conditions of no irrigation. This assessment of water availability within breadbaskets and the likelihood of failure under different irrigation availabilities serves as a first order understanding of water constraints on breadbaskets.

2.5. Breadbasket shifts

We explore potential shifts in breadbaskets in the upcoming decades by comparing increases in AgMIP projected crop yield in new regions relative to yield in existing breadbaskets. The use of GGCMs embedded within GCMs in AgMIP allows us to predict expansion of suitable cropland for specific staple crops as a function of both overall climate and nitrogen. Crop yield is analyzed by $0.5^\circ \times 0.5^\circ$ pixel for breadbasket shifts as opposed to by breadbasket extent for crop yield failure. Nitrogen limitation and historical irrigation are applied. Global crop yields from 1998 to 2017 are reported as percentiles, which allow us to compare relative rather than absolute crop yield across time and space. The global distribution of yield in each future period is then ranked by using percentiles from the 1998 to 2017 period, i.e. present global crop yield distribution.

A breadbasket shift occurs when the future yield percentile rank for a given pixel meets or exceeds the present threshold as calculated from within-breadbasket present percentiles, or global breadbasket mean percentile. For example, the threshold for a breadbasket shift in maize is defined by averaging the present percentiles across all pixels in all maize breadbaskets (US, China, Europe, Brazil, and Argentina). Shifts in maize, soybean, and wheat yields are presented.

3. Results

3.1. Global breadbasket failure and water scarcity

Changes in the probability of a crop yield failure across the global breadbaskets of maize, wheat, rice, and soybean are projected throughout mid-century. Yield failure probability varies by global crop breadbasket with large differences in runs without and with CO_2 fertilization (table 1). Without CO_2 fertilization, the probability of a crop yield failure increases to at least 50% with the exception of wheat (42%) in any given year in 2041–2060. Presently, rice and maize failures are extremely unlikely. By mid-century, a rice or maize failure within global breadbaskets will occur

Table 1. Probability of crop yield failure, defined as at least 10% decline from 1998 to 2017 (present) yield, throughout mid-century in global breadbaskets of maize, wheat, rice, and soybean and respective crop breadbaskets in the US, India, and China with historical irrigation and nitrogen limitation. Synchronous indicates the probability of a synchronous failure of all applicable crops (i.e. the co-occurrence of maize, wheat, and soybean failures in the US; wheat, rice, and soybean in India; and all four crops in China and global). First five rows present crop yield failure probabilities without CO₂ fertilization applied. Bottom five rows present probabilities with CO₂ fertilization applied.

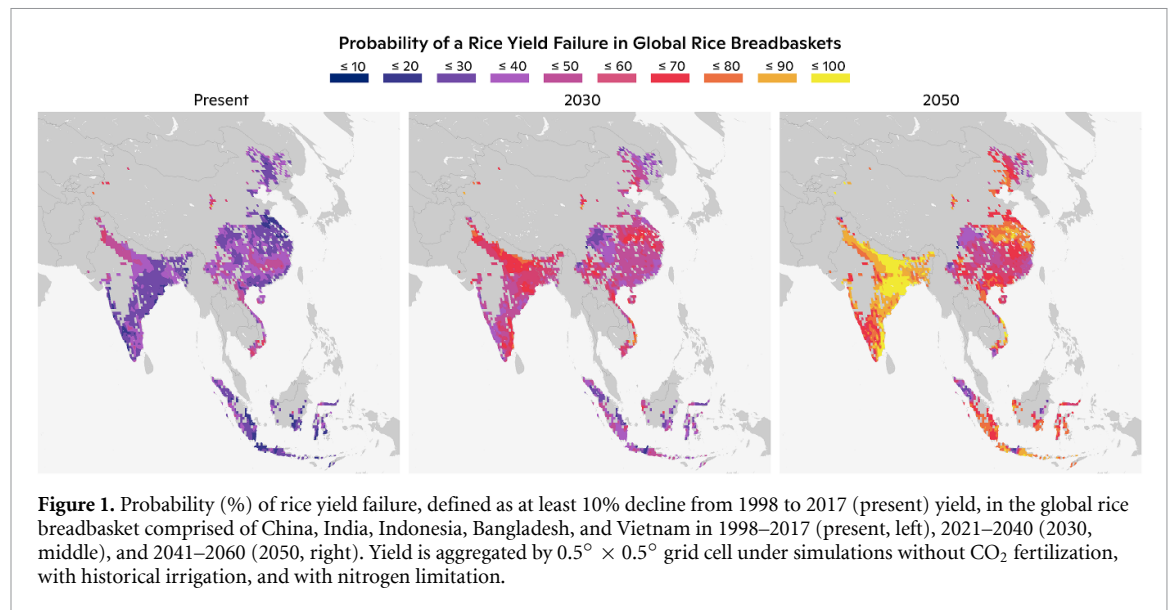
	Global			United States			India			China			
	Present	2030	2050	Present	2030	2050	Present	2030	2050	Present	2030	2050	
Maize	0.07	0.17	0.54	0.14	0.34	0.59	—	—	—	0.1	0.22	0.2	Without CO ₂ fertilization
Wheat	0.02	0.09	0.42	0.21	0.38	0.68	0.12	0.48	0.82	0.09	0.39	0.65	
Rice	0.02	0.08	0.5	—	—	—	0.08	0.22	0.74	0.02	0.13	0.3	
Soybean	0.12	0.4	0.81	0.27	0.48	0.74	0.27	0.38	0.57	0.09	0.19	0.43	
Synchronous	0	0	0.09	0.01	0.06	0.3	0	0.04	0.35	0	0	0.02	
Maize	0.01	0.19	0.31	0.23	0.3	0.49	—	—	—	0.11	0.15	0.08	With CO ₂ fertilization
Wheat	0.03	0.02	0.04	0.2	0.24	0.32	0.34	0.5	0.77	0.12	0.2	0.14	
Rice	0.03	0	0.05	—	—	—	0.09	0.11	0.27	0.02	0.07	0.06	
Soybean	0.13	0.2	0.22	0.29	0.37	0.57	0.27	0.29	0.39	0.07	0.01	0.03	
Synchronous	0	0	0	0.01	0.03	0.09	0.01	0.02	0.08	0	0	0	

at least every other year. The global soybean breadbasket faces the greatest probability of failure with an 81% chance of occurring in any given year by mid-century. This is nearly seven times more likely than in the present. A global soybean breadbasket failure would result in a loss up to 28 million tons, or nearly 9% of the world's soybean, based on average 2013–2017 production from the FAO. Based on the CDF in supplementary figure 1, the global soybean breadbasket also has a 38% chance of a failure of at least 20% decline in yield. A failure of this magnitude would result in a loss of up to 18% of global soybean production. With CO₂ fertilization, failure probabilities are greatly reduced, and the threat of wheat and rice failures is nearly diminished. Yet, even with potential benefits of CO₂, projections of maize and soybean failures still increase by a factor of 3.1 and 1.7 respectively by 2050. Not only do we see an increase in failure probability over time without CO₂ fertilization, we also see a decrease in surplus probability, or at least 10% increase in yield (supplementary table 3). Presently, the probabilities of a yield failure and a yield surplus are commensurate. However, this relationship will skew towards more yield failures in the future, as the probability of a surplus becomes zero for all crops by mid-century. Global synchronous failure of maize, wheat, rice, and soybean across respective global breadbaskets becomes a possibility in 2050 without CO₂ fertilization, projected to occur one in every 11 years.

Though failure probability under scenarios without CO₂ fertilization increases across global breadbaskets, there is spatial variation of failure probability within and between national breadbaskets. We focus on runs without CO₂ fertilization due to the short time horizon of this study and observational evidence of a decline in the CO₂ fertilization effect (Wang *et al* 2020). Figure 1 presents rice failure probability across breadbaskets in China, India Indonesia, Bangladesh, and Vietnam through 2050.

Wheat, soybean, and maize failure probability maps can be found in supplementary figures 3–5. Though the mid-century probability of global rice breadbasket failure is one in every two years, the likelihood of failure is almost every year in parts of China, India, Bangladesh, and Vietnam. Similar to the global rice breadbasket, the mid-century failure probability within maize breadbaskets of Brazil, the US, Europe, and China nears 100% though the global maize breadbasket failure is 54% (supplementary figure 3). Across global soybean breadbasket, there can be a large range of failure probability even within a national breadbasket, as seen in Brazil (supplementary figure 4). This is also seen in the Chinese wheat breadbasket where mid-century failure probability can be as high as 94% in the Northern China Plain and as low as 11% in Chongqing (supplementary figure 5). Spatial variation of crop failures can be expected within breadbaskets due to various regional climates.

Cross-referencing the WSI with historical crop production, 29% of soybean, 46% of rice, 50% of maize, and 65% of wheat produced across the respective global breadbaskets faces high water scarcity. Supplementary figure 6 presents global breadbaskets of maize, wheat, rice, and soybean and the variation of water scarcity across breadbaskets. With the exception of soybean, crop yield failures in 2030 are more likely to occur in high water scarcity regions of global breadbaskets (1.6–3.3 times more likely; see supplementary table 4) as compared to the entire global breadbasket. Low water scarcity, defined as below the 60th percentile corresponding to less than 10% water stress, is observed primarily in Southern Hemisphere breadbaskets, like Brazil and Argentina soybean and maize. Sufficient available water for irrigation is necessary to avoid greater risks of global breadbasket failures, especially for wheat. In scenarios without irrigation or CO₂ fertilization, a global wheat breadbasket failure becomes the most likely out of



the four crops occurring almost every year by 2050 (table 2). In scenarios with sufficient water for irrigation, wheat failures are the least likely out of the four crops. Maize, rice, and soybean breadbasket failures also increase in likelihood without irrigation. This in turn increases the probability of a synchronous global breadbasket failure in 2050 from 9% with sufficient water for irrigation to 37% without irrigation. The likelihood of a synchronized failure event increases from once every eleven years to once every three years. The majority of the high water scarcity areas for each global breadbasket is concentrated in three agricultural powerhouses: the US, India, and China.

3.2. National breadbasket failure

The probability of crop yield failures within the US, India, and China breadbaskets is presented as each nation is a major contributor to global production of multiple crops (supplementary table 1). The US contributes the largest percentage globally of both soybean (34%, or 108 million tons yr⁻¹) and maize (34%, or 363 million tons yr⁻¹). It is also the top fifth contributor of global wheat (8%, or 56 million tons yr⁻¹). India ranks as the second largest producer of rice, third largest of wheat, and fifth largest of soybean in the world. India produced 21% of the world's rice (161 million tons yr⁻¹), 13% of the world's wheat (93 million tons yr⁻¹), and 3% of the world's soybean (11 million tons yr⁻¹). China is the only country that is a top producer of all four major crops. China is the top rice producing country (28%, or 211 million tons yr⁻¹). It is second to the US in global maize production (23%, or 246 million tons yr⁻¹) and second to Europe in global wheat (18%, or 130 million tons yr⁻¹). China's smallest contribution is to global soybean (4%, or 11 million tons yr⁻¹), yet still ranks as the fourth top producer.

3.2.1. United States

The soybean and maize breadbaskets in the US span primarily over the Great Plains and Midwest while the wheat breadbasket is concentrated over the Great Plains (supplementary figure 6). The probability of yield failure becomes 2.7–4.2 times more likely without CO₂ fertilization compared to 1.6–2.1 times more likely with CO₂ fertilization (table 1). By mid-century without CO₂ fertilization, it is more likely that a yield failure will occur than the present average yield for all three crops. The probability of maize, wheat, and soybean failures increases to at least every other year (50%–81%). This remains true for soybean and maize even with CO₂ fertilization, translating to a decline up to 3.4% in both global soybean and maize production—or nearly 11 and 36 million tons, respectively—based on average US contribution to global production from 2013–2017. Wheat failure probability increases from one in every five years in the present to one in every three years by mid-century with CO₂ fertilization. Synchronous failure of US wheat, maize, and soybean is likely to occur every three years by mid-century without CO₂ fertilization. The probability of crop failures of even higher magnitude also increases regardless of CO₂ fertilization. A crop failure event on the magnitude of the 2012 drought (at least 25% decline in yield) is likely to occur at least every other year for soybean and between every two to three years for wheat and maize (supplementary table 5). In 2019, the US was the second top exporter of wheat, soybean, and maize (FAO 2019). US breadbasket failures of 10% and 25% decline will likely impact global markets, as seen with sky-rocketed US export maize prices during the 2012 drought (US Bureau of Land Statistics 2012).

Overall, the US faces the least water scarcity out of the three multi-breadbasket nations. Yet, more than half of wheat (57%), two-fifths of maize (43%),

Table 2. Probability of crop yield failure, defined as at least 10% decline from 1998 to 2017 (present) yield, throughout mid-century in all respective global breadbaskets of maize, wheat, rice, and soybean and respective crop breadbaskets in the United States, India, and China with no future irrigation and with nitrogen limitation. Synchronous indicates the probability of a synchronous failure of all applicable crops (i.e. the co-occurrence of maize, wheat, and soybean failures in the US; wheat, rice, and soybean in India; and all four crops in China and global). First five rows present crop yield failure probabilities without CO₂ fertilization applied. Bottom five rows present probabilities with CO₂ fertilization applied.

	Global			United States			India			China			
	Present	2030	2050	Present	2030	2050	Present	2030	2050	Present	2030	2050	
Maize	0.07	0.44	0.69	0.14	0.43	0.67	—	—	—	0.1	0.3	0.43	Without CO ₂ fertilization
Wheat	0.02	0.85	0.98	0.21	0.5	0.79	0.12	1	1	0.09	0.85	0.91	
Rice	0.02	0.02	0.65	—	—	—	0.08	0.42	0.8	0.02	0.26	0.45	
Soybean	0.12	0.48	0.84	0.27	0.48	0.74	0.27	0.4	0.58	0.09	0.34	0.57	
Synchronous	0	0.04	0.37	0.01	0.1	0.39	0	0.17	0.46	0	0.02	0.1	
Maize	0.1	0.26	0.4	0.23	0.35	0.54	—	—	—	0.11	0.22	0.14	With CO ₂ fertilization
Wheat	0.03	0.17	0.11	0.2	0.31	0.41	0.34	0.88	0.92	0.12	0.77	0.68	
Rice	0.03	0.03	0.14	—	—	—	0.09	0.2	0.44	0.02	0.11	0.06	
Soybean	0.13	0.22	0.24	0.29	0.37	0.57	0.27	0.3	0.42	0.07	0.17	0.07	
Synchronous	0	0	0	0.01	0.04	0.13	0.01	0.05	0.17	0	0	0	

and one third of soybean (33%) historically produced in breadbaskets faces high water scarcity. High water scarcity in the US breadbaskets is primarily driven by three hydrological indicators in the index. (a) Historical drought risk is relatively high and widespread throughout the Midwest. (b) Environmental flow limits due to groundwater pumping have already been reached in many regions in the Plains and Midwest. (c) Over the Ogallala Aquifer, future water stress ranks as one of the highest in the world with a mean value of 534%.

These trends will only worsen in the near-term. For example, DeLucia *et al* (2019) found that maintaining present-day Midwestern US maize yields in 2050 will require an expansion of irrigated lands from 109 000 km² to 509 000 km² as vapor pressure deficit increases. This is supported by AgMIP simulations without irrigation or CO₂ fertilization effects, where the mid-century probability of maize failures will increase to 67% compared to 59% with sufficient water to irrigate (table 2).

3.2.2. India

Collectively, India's three crop breadbaskets span across most of the country (supplementary figure 6). Notable states include Madhya Pradesh, which is part of the soybean and wheat breadbaskets, and Punjab, which is part of the rice and wheat breadbaskets. Out of the three crops, wheat in India experiences the highest mid-century probability of yield failure, regardless of CO₂ fertilization effects (table 1). Wheat failures are projected to occur at least every other year by 2050. This could be driven by a heat-stressed climatic shift in the Indo-Ganges Plains where the wheat breadbasket is located (Ortiz *et al* 2008). The rice breadbasket is the most sensitive to CO₂ fertilization out of India's three breadbaskets. In runs without CO₂ fertilization, rice failure becomes nine times more likely by mid-century versus three times more likely

with CO₂ fertilization. Without CO₂ fertilization, rice and soybean failures, like wheat, are projected to occur at least every other year by mid-century. Synchronous failure of wheat, rice, and soybean is likely to occur every three years by mid-century without CO₂ fertilization. Failures of greater magnitude will increase in likelihood as well. The probability of at least 25% decline in yield will increase from 0% to 16% and 19% by mid-century for wheat and rice respectively (supplementary table 5).

Much of India's breadbaskets face high water scarcity because India ranks worst globally across multiple hydrological variables. Nearly all (95% and 97%) of soybean and wheat historically produced in India's breadbaskets is located in high water scarcity versus 71% of rice historically produced in the breadbasket. In the Northwest, historical water stress and water depletion are among the highest in the world and will continue to rank in the highest water stress in 2030. The entire country ranks the worst in historical drought risk and future seasonal variability. States that are breadbaskets for multiple crops, such as Madhya Pradesh and Punjab, are vulnerable to high water scarcity due to high water stress driven by irrigation demand. 80% of Punjab cropland rotates between growing rice during the monsoon season (*kharif* season) and wheat during the dry season (*rabi* season). In this region, the water demand for rice affects the water availability for wheat (Sharma *et al* 2018). Wheat and rice are India's most important crops as well as the most water intensive. Without future irrigation or CO₂ fertilization, the probability of a wheat failure in India becomes 100% by 2030, which is more than double the probability than with adequate water supply (table 2). A wheat failure would result in a loss up to 9 million tons, or 1% of the world's wheat, based on average 2013–2017 production from the FAO. The likelihood of rice failure in 2030 is almost double without irrigation (42%) compared to with

sufficient irrigation (22%). Rice failures would have a large impact on both local food shortages and global rice markets, as India is the leading rice exporter (FAO 2019). An Indian rice breadbasket failure would result in a decline up to 2.1% in global rice production, or a 16 million ton loss according to average 2013–2017 production. Irrigation played a crucial role for the expansion of wheat and overall increase in yields in India, but increasing water scarcity will strain water supplies with direct implications for breadbasket failure risk and ability to irrigate existing croplands (Zaveri and Lobell 2019). The increasing likelihood of breadbasket failures in India threatens the country's self-sufficiency in production, suggesting potential necessity for imported crops.

3.2.3. China

China's breadbaskets are primarily located in the more populous eastern half of the country (supplementary figure 6). Major multi-breadbasket regions are found in the Northeastern Plain, Northern China Plain, and Yangtze Plain. Out of the three multi-breadbasket nations, China's breadbaskets seem to be the most sensitive to CO₂ fertilization effects on crop yield failure probability. Without CO₂ fertilization, the probability of crop yield failure at least doubles by 2030 for all crops (table 1). By 2050, failure probability increases to between once every five years to at least every other year. Becoming seven times more likely than present probability, wheat failure in China has the highest failure likelihood out of the four crops. Rice failure experiences the greatest relative increase from one in every fifty years to one in every three to four years. The increased likelihood of breadbasket failures in China without CO₂ fertilization may reduce its self-sufficiency, particularly in rice, China's top exporting crop, and wheat. China is already the top importer of agricultural goods, with soybean as its top imported crop (USDA 2020). China is projected to increase soybean and maize imports in the upcoming decade to meet projected demand (Huang *et al* 2017). Reduction in domestic production through breadbasket failures may further increase imports. The increase in breadbasket failure across all crops is not found with CO₂ fertilization. Maize and soybean failures actually decrease in probability while wheat and rice failures minimally increase. The probability of a soybean failure is diminished with CO₂ fertilization compared to without CO₂ fertilization.

The majority of the soybean, wheat, and maize breadbaskets are in the Northern China Plain, the most concentrated region of high water scarcity in the country. At least three-fourths of wheat, maize, and soybean historically produced in China's breadbaskets face high water scarcity (91%, 87%, and 75%). Northern China faces one of the highest levels of future water stress driven by both the lack of surface water supply, especially relative to Southern China, and high water demand comparable to Northern

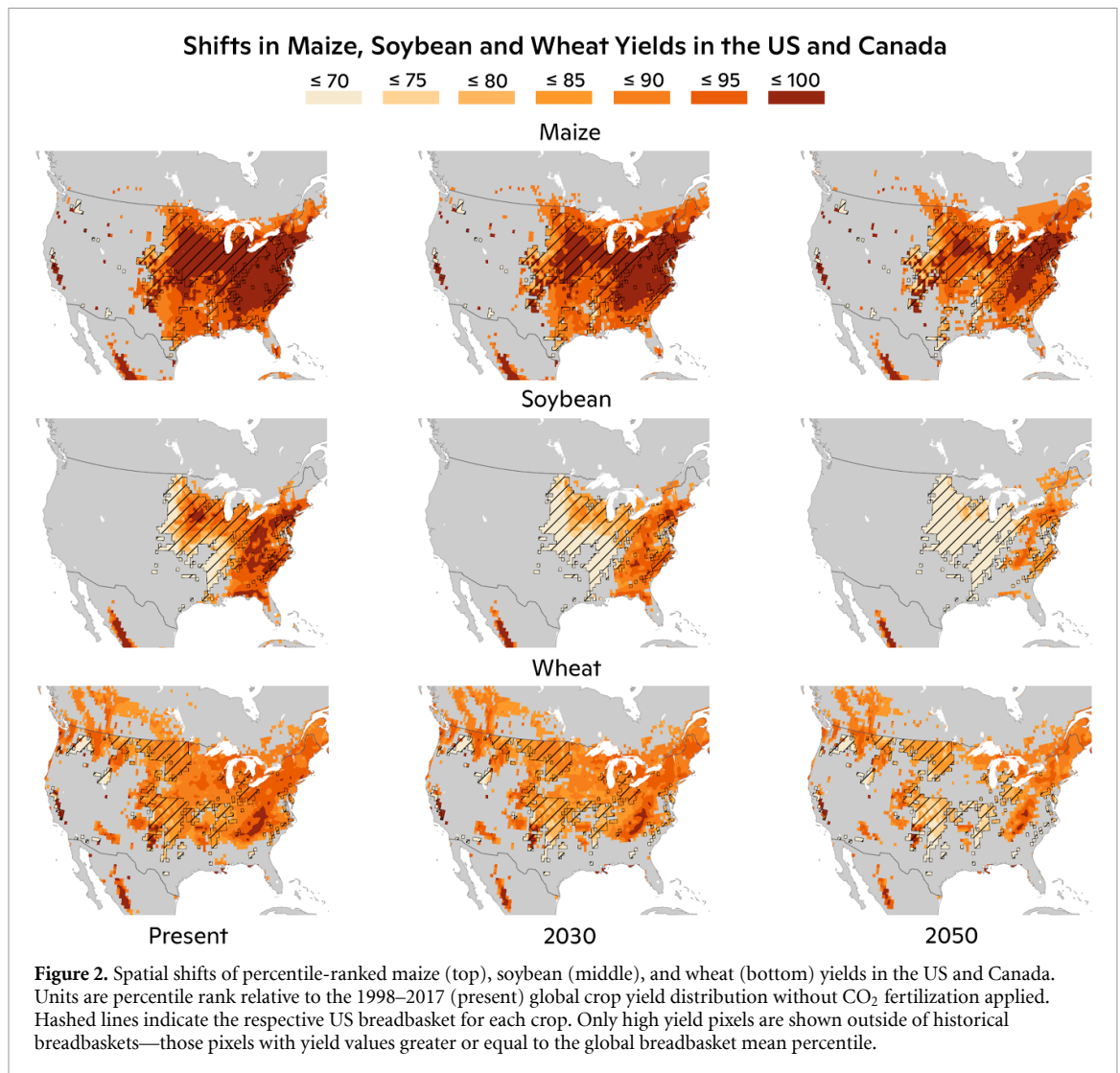
India. In contrast, most of the rice breadbasket is in the water-rich, rain-fed Southeast where the WSI score is roughly in the 50th percentile. Most of the rice breadbasket production facing high water scarcity is in Northern China. The driving variable for high water scarcity for rice is the moderate historical drought risk that affects the entirety of China. Crop yield failures are more likely to occur in China if adequate water supply for irrigation becomes unavailable. By 2050, without CO₂ fertilization, maize failures will occur every two years without irrigation compared to every five years with irrigation and rice failures every two years compared to every three years (table 2). Wheat failures are likely to occur every year without irrigation.

3.3. Breadbasket shifts

Though the US has historically been a top producer of major grains with an agricultural hub centered around the Great Plains and Midwest, climatic conditions favorable to growing wheat, soybean, and maize will expand northward across the Canadian-US border (figure 2). Maize, soybean, and wheat breadbasket shifts are observed by comparing where future yield values meet or exceed the 1998–2017 (present) global breadbasket mean percentile. We note that this is an optimistic treatment of breadbasket shifts as the mean percentile rank across the respective global breadbaskets decreased from present to mid-century for each crop.

The present high-yielding land simulated by AgMIP is largely in agreement with the present US breadbaskets. Supplementary figure 8 shows the range of percentile rank of present yield within each breadbasket. While there are outlying values in each breadbasket—for maize, one pixel is at the 8th percentile globally—the majority of all three US breadbaskets are high yield areas. For example, 95% of the simulated present yield in the maize breadbasket ranks in the 80th percentile or higher (supplementary figure 8). The discrepancy between observed highly productive areas and simulated low-yielding areas is linked to variations among crop models in the AgMIP ensemble and topographic constraints not captured in the models (supplementary figure 2). In addition, present cultivated land is not fully optimized for maximum production (Davis *et al* 2017). Nevertheless, more than half of each present breadbasket ranks higher than the respective global breadbasket mean percentile which defines breadbasket shifts. The following results on shifts in breadbaskets do not include CO₂ fertilization effects on crop yield.

Shifts in maize are defined by global maize breadbasket mean percentile (85th percentile). The mean percentile in the US breadbasket decreases from the 93rd to the 87th percentile from present to 2050. This decline is prominent in the Midwest. In the South Great Plains, some areas yield less than the global maize breadbasket mean percentile in 2050. Across



the border, there is an expansion of high-yielding land in Canada. In Southern Ontario and Quebec, high-yielding land expands roughly 200 km northward. Eighty-nine percent of Canada's maize is currently grown in these two provinces, and thus will likely already have infrastructure in place to support higher crop yields and production (USDA 2018a).

The global soybean breadbasket mean percentile (81st percentile) is the lowest of the three crops. While the global soybean breadbasket mean percentile dropped by a decile from present to 2050, the US soybean breadbasket mean percentile dropped twice as much. By mid-century, almost the entire breadbasket ranks below the 81st percentile, supporting the vulnerability of US soybean growers to meet historical yield levels as the probability of US soybean breadbasket failure increases through mid-century. A soybean shift across the border similar to maize is seen again primarily in Quebec which already produces 16% of Canada's soybean (USDA 2018b).

Wheat yield shifts are based on the 82nd percentile. In the US wheat breadbasket, there are declines

in yield that drop below this threshold, as seen in the South Great Plains again, and declines in yield that become lower than yields in Canada, as seen in the North Great Plains. In Canada, there is a decrease in wheat yield in Saskatchewan and Manitoba, but also yield increases in British Columbia and Alberta.

When CO₂ fertilization effects are included in simulations, more high-yielding land emerges in Canada for all crops, with the greatest land expansion occurring for wheat (supplementary figure 9). The US soybean breadbasket still shifts out of the existing region, but US maize and wheat breadbaskets are largely preserved. However, the recent observed decline of the CO₂ fertilization effect across the globe indicates simulations without CO₂ fertilization may be closer to reality, especially in the short time horizon of this study (Wang *et al* 2020). The scenario of breadbasket shifts with CO₂ fertilization showing both expansion and preservation could represent an optimistic future given adaptive strategies, such as crop cultivar breeding, in response to a changing climate.

The breadbasket shifts in North America follow the narrative expected with climate change—northward expansion of arable land will benefit agriculture in higher latitude countries. The emerging high-yielding croplands in Canada are just as volatile year-to-year as the existing breadbaskets in the US (supplementary table 6). However, there is no emergence of yield similar to today's breadbaskets in Russia. While there is certainly emergence of new agricultural land determined primarily by climate, the amount of yield ranks at the 30th percentile at best, but often lower. Boreal soil types like podzol are typically unfavorable for crop-growing due to low fertility (Altdorff *et al* 2017). It is likely soil quality will be a critical limiting factor in the northward expansion of high-yielding cropland. No significant spatial changes in maize, soybean, or wheat breadbasket shifts out to mid-century were found in the other multi-breadbasket nations, China and India. These breadbaskets will remain confined to high water scarcity locations according to our results, unlike the breadbasket in North America which will shift to areas of lower water scarcity. British Columbia, Ontario, and Quebec score well below the low water scarcity threshold of the WSI (supplementary figure 10). Some regions with high yields, such as Appalachia, may have suitable climate and soil for growing crops, but in reality, have topographic limitations not captured by the AgMIP ensemble.

4. Discussion and conclusion

The probability of maize, rice, soybean, and wheat yield failures across global and national breadbaskets will increase in the upcoming decades. Failure probability is much higher across all crops and all breadbaskets in simulations without CO₂ fertilization compared to with CO₂ fertilization. Comparing results with and without CO₂ fertilization sets a rough bound for the likelihood of crop failures in a changing climate. Because of the hypothesized positive response of crop yields to CO₂, results with CO₂ fertilization could be interpreted as a proxy for what is possible given agricultural technology, use of GMOs, or other human intervention not included in AgMIP. Results without CO₂ fertilization are more realistic for the near-term focus of this study.

Without CO₂ fertilization, the likelihood of wheat, maize, rice, and soybean failures across global breadbaskets increases to at least every other year by mid-century. In multi-breadbasket nations, crop yield failures will occur at least one in every five years starting in 2030 with the exceptions of rice and soybean in China. India's breadbaskets will experience the greatest likelihood of crop failures followed by the US and China. Synchronous failures of crops in global and national breadbaskets presently have a zero probability. By mid-century, synchronous failure is

likely to occur every eleven years across global crop breadbaskets and every three years in the US and Indian crop breadbaskets, separately. While we focus on crop failures as at least 10% decline from present yield, failures of greater magnitude are also projected to increase by mid-century, primarily in the US and India. While the present-day likelihood of crop yield failures is less than that of crop yield surpluses, this relationship will shift as the probability of failure increases.

The WSI reveals that large areas of the present-day global maize, soybean, rice, and wheat breadbaskets are facing high water scarcity. Crop yield failures in high water scarcity areas of breadbaskets are as likely or more likely to occur than failures across the entire breadbasket. Irrigation intensification and expansion are two techniques considered to increase agricultural production in a changing climate. However, without enough water to irrigate existing irrigated croplands, the probability of a crop yield failure becomes greater across all breadbaskets. Water scarcity in breadbaskets will only become worse with shifting precipitation patterns due to climate change and potential irrigation intensification to close yield gaps. Implementation of more efficient irrigation techniques, such as drip irrigation, will be a necessary step in addressing water scarcity, particularly in areas of low water use efficiency and shrinking water supply. Development of low cost, high efficiency irrigation techniques will be a crucial and rewarding challenge in order to reduce economic barriers for small scale farmers around the world.

By mid-century, expansion of suitable climate will encourage higher yields across national boundaries in North America and reduce yields in present-day US wheat, soybean, and maize breadbaskets. Potential gains in cropland expansion presented here are predicated on sufficient soil fertility in previously unarable/uncultivated land. In addition, potential negative impacts on biodiversity, water resources, and carbon storage, especially in high latitude regions, should be strongly considered by decision-makers prior to land-use change (Sanderman *et al* 2017, Hannah *et al* 2020).

Though there is potential for shifts in cropland, breadbaskets that have historically provided the global food system with large quantities of one or more major crops will face challenges in continuing to do so due to changes in climate and growing water scarcity. While a crop failure may have significant impacts on economy and food supply, it does not necessarily translate to the abandonment of cultivated land in existing breadbaskets. Identifying a 'point of no return' of reoccurring failures is a necessary continuation of this research. Agricultural production should not be the sole consideration when expanding agricultural land. When or where it is more beneficial to build new agricultural systems, relative to other ecosystem services, in newly suitable croplands versus

continuing to grow in existing breadbaskets is still poorly constrained.

It should be noted that projections in crop yield failure and shifting breadbaskets do not account for changes in technology, cultivar development, or other adaption strategies. For example, optimized crop redistribution within existing croplands has the potential to not only reduce rainwater and irrigation water consumption, but also feed up to hundreds of million more people (Davis *et al* 2017). Future work should assess whether crop redistribution would change the configuration of current global breadbaskets and what potential yield gains, if any, are to be made. Another high-priority adaptation strategy is the breeding of heat-tolerant crop varieties to mitigate negative impacts of increased temperatures on current breadbaskets (Tigchelaar *et al* 2018). Our results support the necessity for genetic advances in crop heat tolerance as well as crop water efficiency. Further research should explore how much yield loss due to changes in climate can be offset by the implementation of such crop varieties in current breadbaskets.

The increasing risk of breadbasket failures identified in this paper has the potential to disrupt global market prices, import and export relationships, and self-sufficiency. Failure projections presented here do not account for economic or political actions, such as market adjustments or trade bans, which alone can cause food supply declines. Breadbasket failures in this study reflect changes in supply solely from changes in climate and water supply. First and foremost, drastic reduction of CO₂ emissions, especially in the multi-breadbasket nations, is necessary for mitigating risks of breadbasket failures. The impact of breadbasket failures will be global due to high geographic concentration of crop production and the economic power of multi-breadbasket nations. This work supports the need for global cooperation in addressing food security and accessibility. A global maize, rice, or wheat breadbasket failure of at least 10% decline in yield could result in at least 5% calorie supply decline for 6.5–6.8 million people already below the poverty line (d'Amour *et al* 2016). High stock-to-use ratios could curb the impact of a breadbasket failure, but to avoid local food insecurity, high stock in nations that rely on imported staple crops must be prioritized as opposed to top producing and exporting nations. Throughout the ongoing COVID-19 pandemic, we see that grain production declines coupled with export restrictions and aggressive stock-up attempts could severely impact food security in low- and middle-income countries (Falkendal *et al* 2021). Recurring breadbasket failures have the potential to catalyze dramatic changes in import and export flows in the global agricultural market. The consequence of global breadbasket failures mirrors an overarching theme of the climate crisis—the most vulnerable populations will be hit the hardest. With

such an event expected to occur at least every other year by mid-century, international governance organizations need to prepare for global breadbasket failures now, and in such a way that centers on the people who will be most adversely impacted.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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