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RESEARCH ARTICLE

Global reductions in manual agricultural work capacity due to climate change

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Abstract

Manual outdoor work is essential in many agricultural systems. Climate change will make such work more stressful in many regions due to heat exposure. The physical work capacity metric (PWC) is a physiologically based approach that estimates an individual's work capacity relative to an environment without any heat stress. We computed PWC under recent past and potential future climate conditions. Daily values were computed from five earth system models for three emission scenarios (SSP1-2.6, SSP3-7.0, and SSP5-8.5) and three time periods: 1991–2010 (recent past), 2041–2060 (mid-century) and 2081–2100 (end-century). Average daily PWC values were aggregated for the entire year, the growing season, and the warmest 90-day period of the year. Under recent past climate conditions, the growing season PWC was below 0.86 (86% of full work capacity) on half the current global cropland. With end-century/SSP5-8.5 thermal conditions this value was reduced to 0.7, with most affected crop-growing regions in Southeast and South Asia, West and Central Africa, and northern South America. Average growing season PWC could falls below 0.4 in some important food production regions such as the Indo-Gangetic plains in Pakistan and India. End-century PWC reductions were substantially greater than mid-century reductions. This paper assesses two potential adaptions—reducing direct solar radiation impacts with shade or working at night and reducing the need for hard physical labor with increased mechanization. Removing the effect of direct solar radiation impacts improved PWC values by 0.05 to 0.10 in the hottest periods and regions. Adding mechanization to increase horsepower (HP) per hectare to levels similar to those in some higher income countries would require a 22% increase in global HP availability with Sub-Saharan Africa needing the most. There may be scope for shifting to less labor-intensive crops or those with labor peaks in cooler periods or shift work to early morning.

KEYWORDS

agriculture, climate change, heat stress, labor productivity, mechanization, physical work capacity, thermal environment

1 | INTRODUCTION

Manual outdoor labor is essential in many agricultural systems worldwide. The interactions of the thermal environment (defined by air temperature, solar radiation, humidity, and wind speed) with metabolic activity and clothing can contribute to heat stress and affect the health and productivity of outdoor workers (de Lima et al., 2021; Flouris et al., 2018; Morris et al., 2021; Vanos et al., 2020). Physical work capacity (PWC) begins to decline measurably around 20°C ambient temperature and further diminishes as temperature and humidity rise and exposure to solar radiation increases (Junge et al., 2016), while cooling from wind can reduce these effects. Agricultural workers are at heightened risk of exertional heat stress when manual outdoor work such as land preparation, planting, weeding, and harvesting is required during periods of high ambient heat loads. To defend against hyperthermia, workers slow down to reduce metabolic heat production and the associated rise in body temperature.

The metabolic rate associated with outdoor labor is expected to exceed the work capacity for safe work more frequently as global warming continues (Pörtner, Roberts, Tignor, et al., 2022), increasing the risk of exertional heat illnesses and reducing labor productivity (Dasgupta et al., 2021). Quantifying the occurrence and magnitude of heat stress can improve our understanding of the potential impacts of global climate change on agricultural worker productivity (Vanos et al., 2021).

Recent research in this area includes both global (Andrews et al., 2018; Orlov et al., 2020) and country-specific studies (e.g., Brazil—Alves de Oliveira et al., 2021, India—Koteswara Rao et al., 2020, and Indonesia—Wolff et al., 2021). In this paper, we use a new empirical model of human thermoregulation to estimate world-wide losses in PWC from heat stress from the thermal environment (Foster, Smallcombe, Hodder, Jay, Flouris, & Havenith, 2022; Foster, Smallcombe, Hodder, Jay, Flouris, Morris, et al., 2021; Foster, Smallcombe, Hodder, Jay, Flouris, Nybo, et al., 2022).

PWC is defined as "the maximum physical work output that can be reasonably expected from an individual performing moderate to heavy work over an entire shift" (Foster, Smallcombe, Hodder, Jay, Flouris, Nybo, et al., 2021). It expresses the expected labor output in an environment relative to the output under conditions without heat-stress-related reduction in work performance. For this paper, we report PWC as a fraction with 1.0 equivalent to work capacity with no heat stress, and 0 indicative of no work being possible due to heat stress.

We computed PWC using all elements for the wet-bulb globe temperature (WBGT) estimation (ambient temperature, relative humidity, incident solar radiation, and wind speed) for bias-corrected daily weather data generated by five earth system models (ESMs) for three emission scenarios and three time periods at a spatial resolution of 0.5°.

2 | METHODS

2.1 | Weather data

We use CMIP6 (Eyring et al., 2016) weather data prepared by the ISIMIP project (www.isimip.org) consisting of bias-corrected standardized weather variables at ½° spatial resolution from five ESMs—GFDL-ESM4, UKESM1-0-LL, MPI-ESM1-2-HR, MRI-ESM2-0, and IPSL-CM6A-LR (Lange, 2019, 2022). These ESMs span the range of climate sensitivity (the predicted rise in global temperature with a doubling of CO_2 relative to pre-industrial levels) in CMIP6 ESMs (Eyring et al., 2016; Meehl et al., 2020). In the five ISIMIP ESMs, the global temperature change from 1983–2013 to 2069–2099 ranges from 0.9 to 2.3°C for SSP1-2.6 and from 2.9 to 5.6°C for SSP5-8.5 (Jägermeyr et al., 2021).

We use ESM data from model runs for three shared socioeconomic pathways (SSP1-2.6, SSP3-7.0 and SSP5-8.5). SSP1-2.6 and SSP5-8.5 provide plausible if unlikely lower and upper bounds on potential future climate conditions. SSP3-7.0 is sometimes considered a business-as-usual scenario. Under SSP1-2.6, greenhouse gas emissions peak in the mid-21st century and then decline, whereas SSP5-8.5 emissions continue to rise through the end-of the 21st century. We use data for three 20-year periods: 1991–2010 ("recent past"), 2041–2060 ("mid-century"), and 2081–2100 ("end-century"). SSP3-7.0 results generally are between the values for the SSP1-2.6 and SSP5-8.5 scenarios.

2.2 | Crop area and cropping season data

We use crop-specific area, circa 2000, from Monfreda et al. (2008). For growing season calculations, we use data from the cropping calendars of Sacks et al. (2010).These come from a variety of sources and time periods but are generally in the early years of the 21st century. For consistency with climate data nomenclature, we refer to these as from the "recent past".

2.3 | PWC computation

The PWC is an advanced empirical model for quantifying the impact of heat stress on work capacity (Foster, Smallcombe, Hodder, Jay, Flouris, Nybo, et al., 2021). The original formula to compute PWC was based on data from more than 300 one-hour human experimental trials in a laboratory setting with varying environmental conditions that encompassed ambient air temperatures from 15 to 50°C, relative humidity of 20%, 50%, and 80%, wind speed from 0.2 to 3.5 m/s, and incident solar radiation from 0 to 800 W/m^2 (Foster, Smallcombe, Hodder, Jay, Flouris, & Havenith, 2022; Foster, Smallcombe, Hodder, Jay, Flouris, Morris, et al., 2021). The ability to include solar radiation in heat stress measurements is essential to estimate true outdoor heat stress as well as model the impact of shade or working in low-to-no sunlight, yet many studies do not include solar radiation, or any variation of such, in their heat stress assessments.

PWC is computed with a thermal load metric that is derived from temperature, relative humidity, wind speed, and incident solar radiation. This can be done with either the WBGT or the Universal Thermal Climate Index (Bröde et al., 2012; Jendritzky et al., 2012). We used WBGT because it is widely used in this literature. We computed the WBGT for each grid cell and each day using the WBGT function in R package meteor (Hijmans, 2023) that provides a fast implementation of the algorithm developed by Liljegren et al. (2008) as implemented by Casanueva (2019).

We computed WBGT for the daytime as that is when most manual agriculture field work is done. To do so we derived the average temperature in daylight hours from the daily minimum and maximum temperature values, taking into account the day of the year and latitude to compute daylength, using the dayTemp function in the meteor R package. While it might be possible to estimate hourly values for more of the input data (see the experimental code in evalHourly.R code available at the paper Zenodo link below), our preliminary experiments suggest that the effects could be either slightly above or below the results with average daily values.

The formula for a 1-h PWC value using WBGT (Foster, Smallcombe, Hodder, Jay, Flouris, Nybo, et al., 2021) is:

$$\mathrm{PWC} = 100 / \left(1 + \left(\frac{33.63}{\mathrm{WBGT}}\right)^{-6.33}\right). \qquad (1)$$

Smallcombe et al. (2022) developed an adjustment for longer exposures using laboratory experiments with six 1-h work-rest cycles with a 1-h break in a full day. Their results were used to adjust 1-h PWC to PWC for a full day (see Smallcombe et al., 2022; Table 2).

The PWC model was developed using young, unacclimatized males performing generic work in climatic chambers, with breaks in a cool environment. Follow-up studies indicate that the high level of physical work performed in the experiments and the use of unacclimated participants may have led to an overestimation of losses, while conversely, the young population (high fitness) use of cool breaks would have led to an underestimation of losses. While these points indicate limitations to the approach, it is currently the best validated model available to describe the impact of heat on generic agricultural work workers (Foster, Smallcombe, Hodder, Jay, Flouris, Morris, et al., 2021; Foster, Smallcombe, Hodder, Jay, Flouris, Nybo, et al., 2022).

We use three metrics to summarize the daily PWC values: the mean annual value, the recent past growing season's weighted mean, and the consecutive 90-day period of a year with the lowest mean PWC, referred to below as the hottest period, approximating the local summer in temperate regions. The growing season weights were computed for each day of the year by determining, for each grid cell and day, presence (1) and absence (0) for each of the 19 annual crops included in the cropping calendars of Sacks et al. (2010) and multiplying by each crop's area planted according to Monfreda et al. (2008). These 19 crops cover 68% of all crop area in the recent past. No changes are made to the growing seasons and crop locations in the future.

PWC values for each day and each model in each of the three time periods are calculated and then averaged by day, first for each 20-year period by scenario and then by model. These averaged daily data are used in the analysis. We report the mean PWC during the recent past agricultural growing seasons and during the 90-day period in a year with the lowest mean PWC. We consider adaptations that involve reduced direct exposure to solar radiation and use of mechanization. More details on the modeling process and the code to download the data and reproduce the results are available at https://zenodo.org/doi/10.5281/zenodo.10429708.

We show more detailed results for selected countries located in different regions of the globe and with varying income levels (Brazil, Nigeria, and India).

2.4 | Workers affected

We estimate the number of agricultural workers in each grid cell where crops were grown in the recent past (Monfreda et al., 2008) using 2020 agricultural labor data collated at the Economic Research Service, USDA (Fuglie et al., 2023). These agricultural labor numbers are divided by the total agricultural area in the recent past. The resulting average number of workers per hectare was multiplied by the cropped area in each grid cell.

2.5 | Adaptation options—Reducing solar radiation and mechanization to reduce hard physical labor

There are several ways to deal with productivity loss in agriculture from climate change. These include interventions such as changing cropping calendars for existing crops or to new crops to shift field work to cooler times of day (or to night, with lights) or year (Kjellstrom et al., 2009), devising methods to reduce exposure to solar radiation (such as shade, more reflective clothing or working at low sun times of day), and increasing the use of machine power in place of human labor. We explore two potential adaptation options—reducing impacts of solar radiation and increasing use of machinery. Solar radiation impacts can be reduced by both changes in the fraction of the radiation that clothing reflects and increasing the extent of work time in shade (Kenny et al., 2008; Morabito et al., 2021). We estimate the theoretical maximum improvement in PWC values from increased shade availability by setting the solar radiation variable to zero in the WGBT computation (e.g., by working at night with lights). This method also allows us to estimate the influence of working at morning, dusk, or overnight when direct solar radiation is very low or zero. The infrastructure and behavioral adaptations are already in use in some locations but will need to increase widely to maintain productivity.

Mechanization is an adaptation that reduces the need for hard physical labor—work for field preparation, planting, weeding, and harvesting needed to grow crops—all of which can take place in the hottest parts of the growing season. Because there are limited data on existing mechanization or on the potential for future mechanization to reduce hard physical labor, we use data on existing mechanization per hectare in high income countries to estimate a rough target for future mechanization in lower income countries with low existing mechanization levels (Fuglie et al., 2023). In high income countries, the ratio of agricultural horsepower (HP) to cropland ranges from 1 to 14. In many low-income countries, the value can be as low as 0.001. We assume a value of 1 provides a lower bound on the HP needed to replace physical labor with equipment and calculate the additional agricultural mechanization needed to bring all countries to that level.

3 | RESULTS

The median crop-area-weighted annual average PWC for the recent past (1991–2010) period was 0.89 of full work capacity. It was 0.68 for regions in the 10th percentile (warmest conditions), and 0.98 for regions in the 90th percentile (coolest conditions). This value ranged from 0.65 to 0.97 during the growing season, and 0.56 to 0.93 during the hottest period of the year (Figure 1; Table 1; Table S1 for country-specific results). In the tropics (between 23°N and 23°S), the median PWC was lower than the global median by between 0.14 (hottest period) and 0.18 (growing season), depending on the temporal aggregation approach (Figure 2; Table S2).

There is a clear difference between the PWC computed for different SSPs for end century conditions, but not for the mid-century thermal environment (Figure 1). Comparing recent past to mid-century results with SSP5-8.5 thermal conditions, the global annually aggregated median PWC for the 50th percentile declines from 0.89 to 0.85. The decline is from 0.86 to 0.80 for the growing season and from 0.76 to 0.67 for the hottest period. For the same thermal conditions in the tropics, the decline is from 0.73 to 0.66 for the annual average, from 0.69 to 0.62 for the growing season and from 0.62 to 0.53 for the hottest period. Under end-century SSP5-8.5 thermal conditions, PWC declines further to 0.78 (annual), 0.70 (growing season) and 0.54 (hottest period) of full capacity.

The greatest declines in PWC occur in the latitudinal range between 20°S to 35°N (Figure 2). The reduction in the hottest season is especially pronounced around 30°N latitude, a band that includes the southern US, North Africa, the Gangetic Plain, and southern China. The western Indo-Gangetic plains in Pakistan and India would see hottest period PWC values of less than 0.3 with end-century/SSP5-8.5 thermal conditions (Figure 3). The growing season aggregates also show sharp declines in PWC values in the parts of the Amazon, the Sahel, and South and Southeast Asia. The lowest growing season PWC values in all time periods are in the tropics and sub-tropics, including in West and Central Africa, South Asia, and most of Southeast Asia.

Relative to the recent past, end-century SSP5-8.5 conditions cause a large expansion of regions with average PWC values below 0.80 (e.g., eastern United States, South Africa, northern China) (Figure 3). Southeast Asia would also see large swaths with an average growing PWC below 0.50. Work capacity would be especially low (<0.50 PWC annual average; <0.40 in the warmest period) in high population areas of northern India, Pakistan, parts of southern China, and Southeast Asia. The SSP3-7.0 results exhibit the same pattern, with smaller reductions.

3.1 | Farm workers affected

The mean of 2018–2020 USDA/ERS estimates of people working in agriculture globally is 856.7 million (Fuglie, Jelliffe, and Morgan,

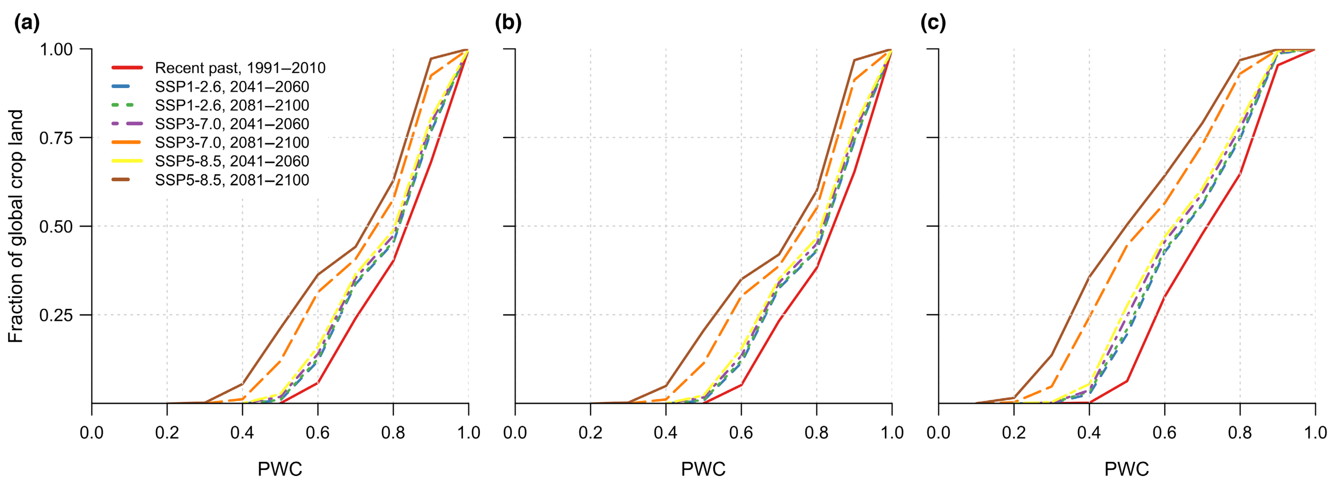

FIGURE 1 Cumulative distribution of recent past cropland physical work capacity (PWC) for recent past and potential future thermal conditions (2041–2060 and 2081–2100, for emission scenarios SSP1-2.6, SSP3-7.0 and SSP5-8.5). The daily PWC values were averaged temporally for (a) the entire year (annual), (b) growing season (weighted by the cropping intensity throughout the year), and (c) the hottest 90 continuous days of the year. They were averaged spatially using recent past global cropland area as weights.

TABLE 1 Physical work capacity (PWC) for 1991–2010 and potential future thermal conditions (2041–2060 and 2081–2100, for three emission scenarios: SSP1-2.6, SSP3-7.0 and SSP5-8.5). The daily PWC values are averaged temporally for an entire year (annual), for the crop-area weighted growing season and for the 90 continuous days of the year with the lowest PWC. They are averaged spatially using the global cropland area in the recent past to compute crop-area weighted percentiles.

Thermal environment, SSP and period	Annual			Growing season			Hottest period		
Area percentile	10	50	90	10	50	90	10	50	90
Historical, 1991–2010	0.68	0.89	0.98	0.65	0.86	0.97	0.56	0.76	0.93
SSP 1–2.6									
2041–2060	0.63	0.86	0.96	0.60	0.82	0.96	0.50	0.70	0.90
2081–2100	0.62	0.86	0.96	0.59	0.81	0.96	0.49	0.70	0.90
SSP 3–7.0									
2041–2060	0.61	0.86	0.96	0.62	0.87	0.96	0.49	0.68	0.89
2081–2100	0.53	0.81	0.94	0.53	0.82	0.94	0.38	0.59	0.83
SSP 5–8.5									
2041–2060	0.60	0.85	0.96	0.57	0.80	0.96	0.47	0.67	0.88
2081–2100	0.48	0.78	0.93	0.45	0.70	0.93	0.32	0.54	0.80

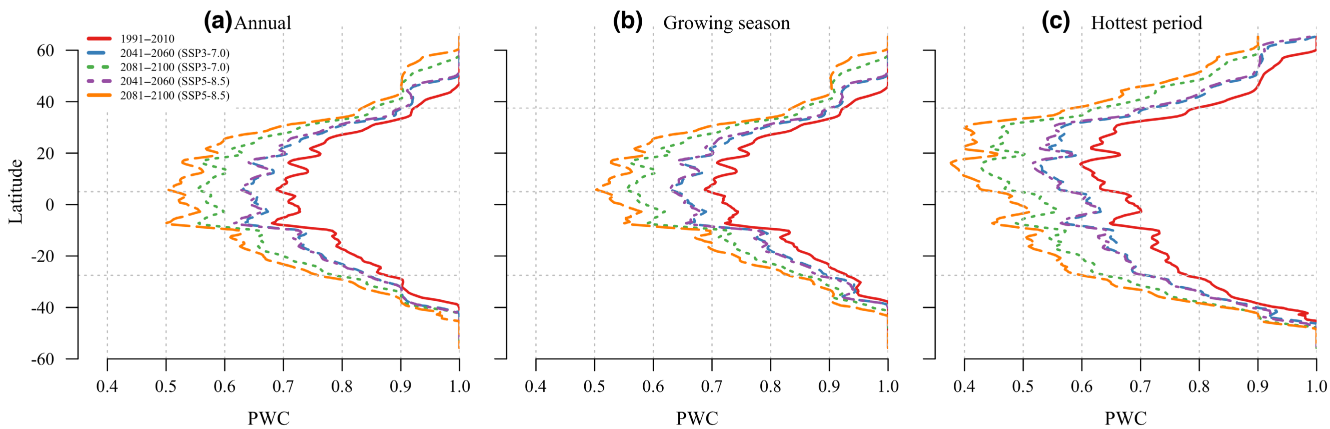

FIGURE 2 Physical work capacity (PWC) by latitude for global cropland for historical (1991–2010) and potential future thermal conditions (2041–2060 and 2081–2100 with SSP3-7.0 and SSP5-8.5). The daily PWC values were averaged temporally for (a) the entire year (annual), (b) growing season (weighted by the cropping intensity throughout the year) and (c) the hottest 90 continuous days of the year.

date accessed 27/02/2023). With the recent past thermal environment, 35% of the agricultural workforce (302 million workers) was in locations where the growing season average PWC was 0.80 of full capacity or less (Table 2). With the end-century/SSP5-8.5 thermal environment, the number of workers affected by those conditions increases to 75% and workers in environments with a growing-season average PWC of 0.60 or less increases from zero to 45%.

3.2 | Country-level analysis

Here, we show results for selected countries located in different regions of the globe and with varying income levels in Table 3 and present growing season maps for three countries—Brazil, Nigeria, and India in Figure 4 to highlight the potential for subnational differences in thermal environments.

Of the selected countries, France has the least losses in PWC from the recent past to the future in all metrics and scenarios; Nigeria, Pakistan, and India generally have the most.

There can be substantial differences within each country (Figure 4), driven by geospatial differences such as elevation and proximity to coastal waters and the temperature of those waters. With end-century/SSP5-8.5 thermal conditions, in Brazil the lowest values are in the northwest (around 0.4) with southwest values the highest (around 0.8). In Nigeria, the variation is smaller, but the lowest values are in the northeast (around 0.4) and highest values in the center (around 0.6). In India, the eastern coast has the lowest PWC values (less than 0.5 for many of these areas) along with Assam in the northeast. The highest values are around 0.7 in the central regions of the country.

At the 0.5 percentile cutoff and with an end-century SSP5-8.5 thermal environment, Brazil has the smallest number of agricultural workers (1.3 million) affected (Table 4). Nigeria has 6.4 million workers and India has 43.2 million workers affected.

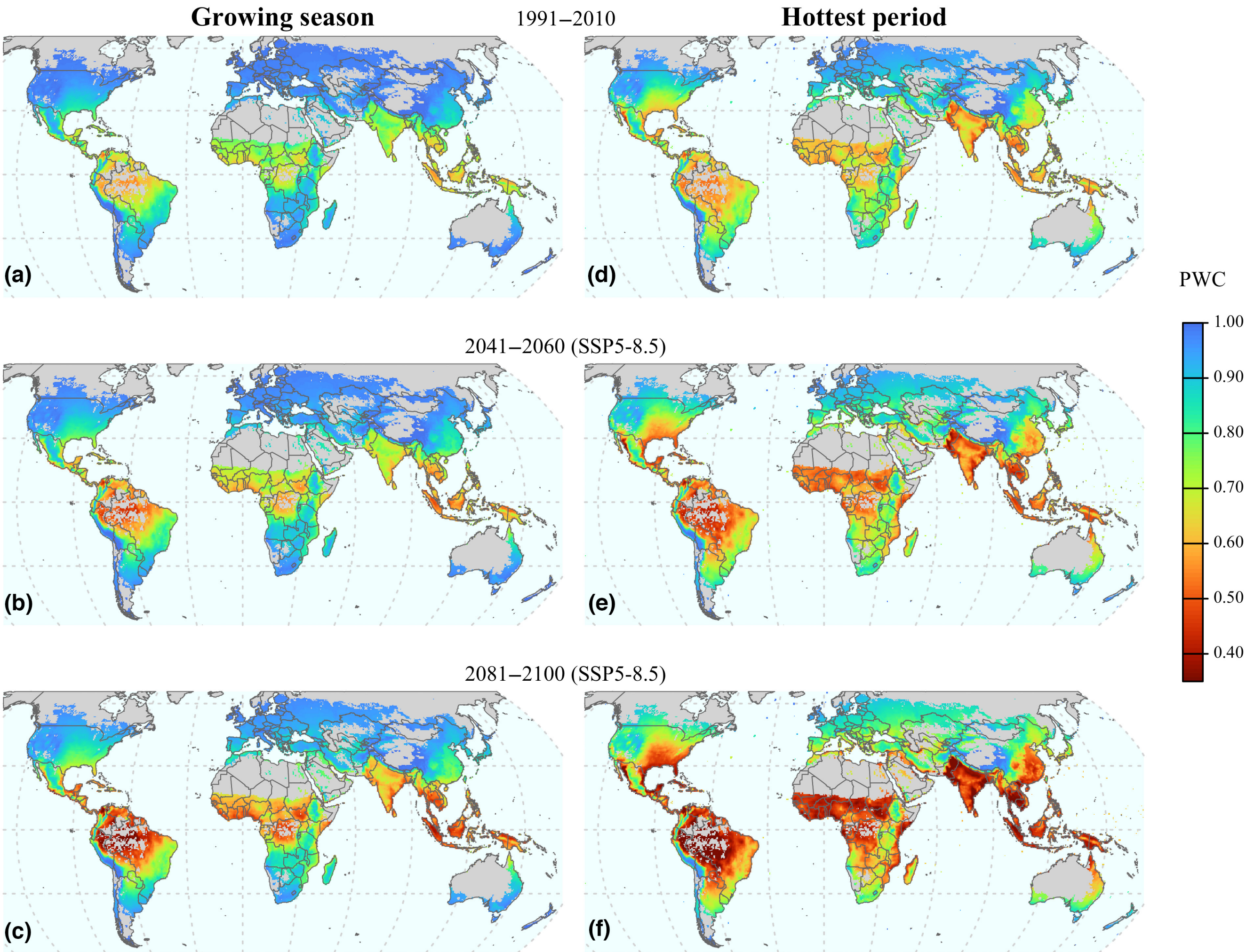

FIGURE 3 Average PWCs during the crop growing season and the hottest period (the hottest 90 continuous days in the year) for three time periods: (a, d) recent past (1991–2010); (b, e) with mid-century (2041–2060) with SSP5-8.5; (c, f) end-century (2081–2100) with SSP5-8.5. Areas with no crops at the start of the 21st century are excluded (gray areas). Map lines delineate study areas and do not necessarily depict accepted national boundaries. PWC, Physical work capacity.

TABLE 2 Share of agricultural workers in the recent past during the crop growing season with mean growing season physical work capacity (PWC) at or below a cutoff value of PWC by period and emission scenario. The total number of workers (856.7 million) is based on the mean of estimates for 2018–2020.

Emission scenario and period	Workers (%)				
PWC percentile	≤0.50	≤0.60	≤0.70	≤0.80	≤0.90
Recent past, 1991–2010	0.0	0.0	2.0	35.3	60.6
SSP1-2.6					
2041–2060	0.0	0.2	14.2	45.6	69.4
2081–2100	0.0	0.2	15.3	46.1	69.7
SSP3-7.0					
2041–2060	0.4	10.1	37.2	57.0	82.0
2081–2100	7.4	30.3	53.8	66.8	89.5
SSP5-8.5					
2041–2060	0.7	11.5	41.9	57.8	83.3
2081–2100	15.7	44.5	56.8	75.0	92.7

Source: Labor data from Fuglie, Jelliffe, and Morgan (date accessed 27/02/2023), PWC values from own calculations.

TABLE 3 Summary of physical work capacity (PWC) results for selected countries with varying income levels for historic, mid-, and end-century in the hottest periods and growing seasons and "Other" data used in adaptation analysis.

Variable	Brazil	China	France	Nigeria	Pakistan	India	United States
PWC, growing season							
Recent past 1991–2010	0.84	0.91	0.97	0.75	0.72	0.77	0.93
SSP3-7.0, 2041–2060	0.80	0.88	0.96	0.69	0.66	0.71	0.90
SSP3-7.0, 2081–2100	0.73	0.84	0.93	0.61	0.58	0.63	0.86
SSP5-8.5, 2041–2060	0.79	0.87	0.95	0.68	0.65	0.69	0.90
SSP5-8.5, 2081–2100	0.70	0.81	0.92	0.56	0.54	0.57	0.84
PWC, hottest period							
Recent past 1991–2010	0.73	0.77	0.92	0.60	0.62	0.54	0.81
SSP3-7.0, 2041–2060	0.66	0.68	0.88	0.53	0.54	0.45	0.73
SSP3-7.0, 2081–2100	0.64	0.81	0.92	0.54	0.57	0.56	0.84
SSP5-8.5, 2041–2060	0.65	0.67	0.87	0.51	0.53	0.42	0.72
SSP5-8.5, 2081–2100	0.53	0.54	0.78	0.37	0.39	0.27	0.59
Other							
Labor[a]	8136	186,285	654	20,057	25,991	190,013	2399
Cropland[b]	76,244	194,611	20,709	61,808	67,487	296,941	233,531
Machinery[c]	43,707	1,399,284	40,429	791	27,633	356,576	160,634
Machinery per agricultural cropland[d]	0.57	7.19	1.95	0.01	0.41	1.20	0.69
Machinery per capita[e]	5.37	7.51	61.79	0.04	1.06	1.88	66.96

Note: See Table S3 for data in the "Other" section for all countries.
[a]000 ag. workers.
[b]000 hectares.
[c]000 horsepower (CV).
[d]Horsepower (CV) per hectare.
[e]Horsepower (CV) per agriculture worker.
Source: Own calculations for PWC and Fuglie, Jelliffe, and Morgan (date accessed 27/02/2023) for labor, cropland, and machinery.

3.3 | Adaptation options

We consider two adaptation options—increasing shade availability and mechanization. The modeled elimination of solar radiation effects provides the outer bound of the potential benefits from shade and lighter clothing. The benefits are largest for the crop area with the lowest PWC values. Consider the area with the lowest PWC values (10th percentile). With the end-century/SSP5-8.5 thermal environment, the average growing season PWC value is 0.45 (Table 1). The improvements with no solar radiation were 0.10 of full capacity (Table 5). In the areas that include the highest average PWC values (90th percentile), the average growing season PWC value is 0.93. When omitting the effect of solar radiation, the PWC increases by 0.02.

The changes are largest near the equator and become smaller in cropping areas closer to the poles (Figure 5). The areas with the greatest improvement in average PWC values include parts of Amazonia, the Sahel and central Africa, and parts of South and Southeast Asia.

The direct benefit of mechanization is reduced hard physical labor. We use agricultural HP availability per hectare as a measure of mechanization. In 2020, the ratio of HP to agricultural crop area was over 10 HP/ha for Japan, Ireland, South Korea, China, and Malta. At the low end of the HP per hectare ratio are 10 countries with 1/100th HP per hectare. Of the countries in Table 3, HP availability per hectare is highest in China, France, and India.

Countries with the greatest required increase in HP per hectare are mostly in a belt across the center of Africa (Figure 6). The additional HP needed to bring all countries to the 1 HP/hectare value is 632 million HP which is an increase of 22.3% over the existing amount.

4 | DISCUSSION

We estimated the potential for severe heat stress in agricultural workers driven by climate change using a recently developed metric—PWC. The PWC approach here is the first that we are aware of that generates quantitative estimates of the loss of work capacity across climate conditions, including more aspects of the weather. We used three approaches to temporal aggregation—average annual, growing season, and the warmest 90-day period

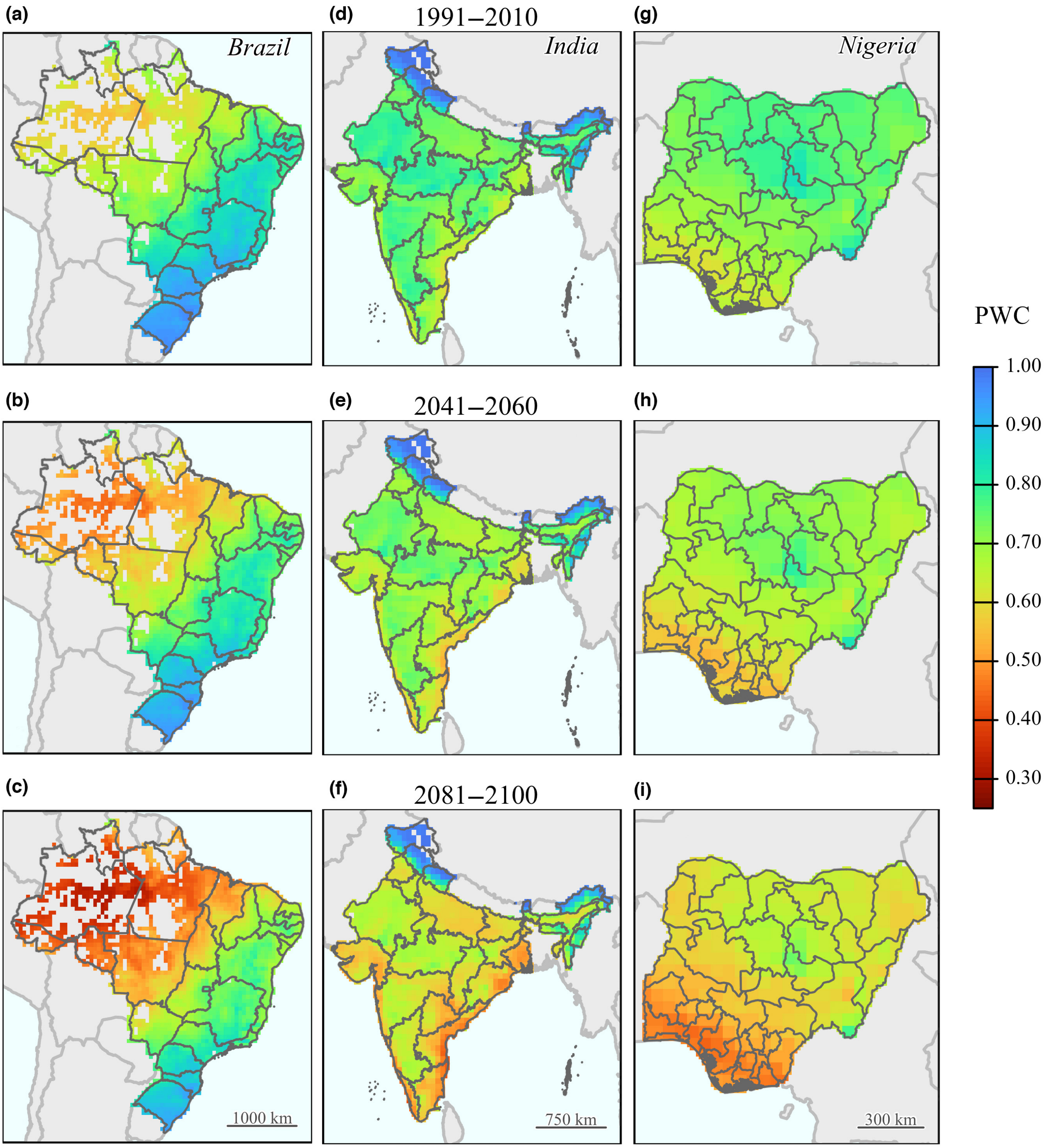

FIGURE 4 Average PWCs during the growing season for three countries (Brazil (a–c), India (d–f), and Nigeria (g–i)) and thermal environments in three periods—recent past (1991–2010) (a, d, g); mid-century (2041–2060) with SSP5-8.5 (b, e, h); end-century (2081–2100) with SSP5-8.5 (c, f, i). Areas where no crops were grown at the start of the 21st century are not considered (gray areas). Map lines delineate study areas and do not necessarily depict accepted national boundaries. PWC, Physical work capacity.

(which has the lowest average PWC value). Our results find PWC values are already well below 1 in parts of the Amazon region in Brazil; West Africa and East Central Africa; much of South and Southeast Asia; and parts of eastern China. In some agriculture-intensive regions, SSP5-8.5, end-century PWC values would be as low as 0.32. Average end-century changes from the recent historical period are as much as 0.24 (derived from Table 1). Country-specific changes during the same period and with hottest period results are as much as 0.27 (India, derived from Table 3). These impacts are pronounced during the hottest period. This is especially

TABLE 4 Agricultural labor in the recent past experiencing growing season thermal environments from different periods and scenarios (000 workers)—Brazil, India, and Nigeria.

Emission scenario and period	Workers (000)				
PWC percentile	0.5	0.6	0.7	0.8	0.9
Brazil					
Recent past, 1991–2010	0	96	1177	3256	8024
SSP1-2.6, 2041–2060	25	491	1996	4757	9552
SSP1-2.6, 2081–2100	25	491	1930	4683	9432
SSP3-7.0, 2041–2060	64	887	2232	5215	9793
SSP3-7.0, 2081–2100	866	1967	4030	7524	11,464
SSP5-8.5, 2041–2060	111	1025	2418	5558	10,246
SSP5-8.5, 2081–2100	1295	2561	5181	9023	11,642
Total agricultural labor, recent past	12,959	12,959	12,959	12,959	12,959
India					
Recent past, 1991–2010	0	621	44,053	235,833	254,772
SSP1-2.6, 2041–2060	0	9560	134,485	249,068	255,976
SSP1-2.6, 2081–2100	0	15,054	147,462	250,485	256,190
SSP3-7.0, 2041–2060	0	17,117	152,309	250,983	256,266
SSP3-7.0, 2081–2100	11,689	116,963	247,295	254,442	258,677
SSP5-8.5, 2041–2060	100	22,845	186,731	251,331	256,727
SSP5-8.5, 2081–2100	43,163	203,580	251,687	255,711	259,273
Total agricultural labor, recent past	261,716	261,716	261,716	261,716	261,716
Nigeria					
Recent past, 1991–2010	0	0	8049	25,668	27,694
SSP1-2.6, 2041–2060	0	3505	14,318	26,714	27,694
SSP1-2.6, 2081–2100	0	3663	14,492	26,714	27,694
SSP3-7.0, 2041–2060	0	4320	17,033	27,085	27,694
SSP3-7.0, 2081–2100	3505	13,714	26,098	27,694	27,694
SSP5-8.5, 2041–2060	0	4467	17,807	27,184	27,694
SSP5-8.5, 2081–2100	6360	20,159	26,828	27,694	27,694
Total agricultural labor, recent past	27,694	27,694	27,694	27,694	27,694

Source: Labor data from Fuglie, Jelliffe, and Morgan, (date accessed 27/02/2023), physical work capacity (PWC) values from own calculations.

TABLE 5 Change in the physical work capacity (PWC) ratio from elimination of the radiation effect in PWC values in the cumulative distribution of PWC for recent past (1991–2010) and potential future thermal conditions (2041–2060 and 2081–2100, for SSP1-2.6 and SSP5-8.5). The daily PWC values are aggregated over annual, growing season, and hottest 90 continuous days of the year.

Emission scenario and period	Annual			Growing season			Hottest period		
PWC percentile	0.1	0.5	0.9	0.1	0.5	0.9	0.1	0.5	0.9
Recent past, 1991–2010	0.08	0.04	0.00	0.08	0.04	0.01	0.09	0.07	0.03
SSP 1–2.6, 2041–2060	0.09	0.04	0.02	0.09	0.05	0.01	0.10	0.08	0.03
SSP 1–2.6, 2081–2100	0.09	0.04	0.02	0.09	0.06	0.01	0.10	0.08	0.03
SSP 3–7.0, 2041–2060	0.09	0.03	0.01	0.08	0.03	0.01	0.09	0.08	0.04
SSP 3–7.0, 2081–2100	0.09	0.05	0.02	0.10	0.04	0.02	0.10	0.10	0.05
SSP 5–8.5, 2041–2060	0.09	0.04	0.01	0.09	0.05	0.01	0.10	0.09	0.04
SSP 5–8.5, 2081–2100	0.10	0.05	0.02	0.10	0.07	0.02	0.11	0.10	0.06

serious in northern India and Pakistan where cropping is done throughout the year. Our results are similar to recent studies. Examples include potential labor capacity reductions of 30%–50% in vulnerable regions of sub-Saharan Africa and Southeast Asia (de Lima et al., 2021) and an 18% average decline in labor globally under 3°C warming (Dasgupta et al., 2021).

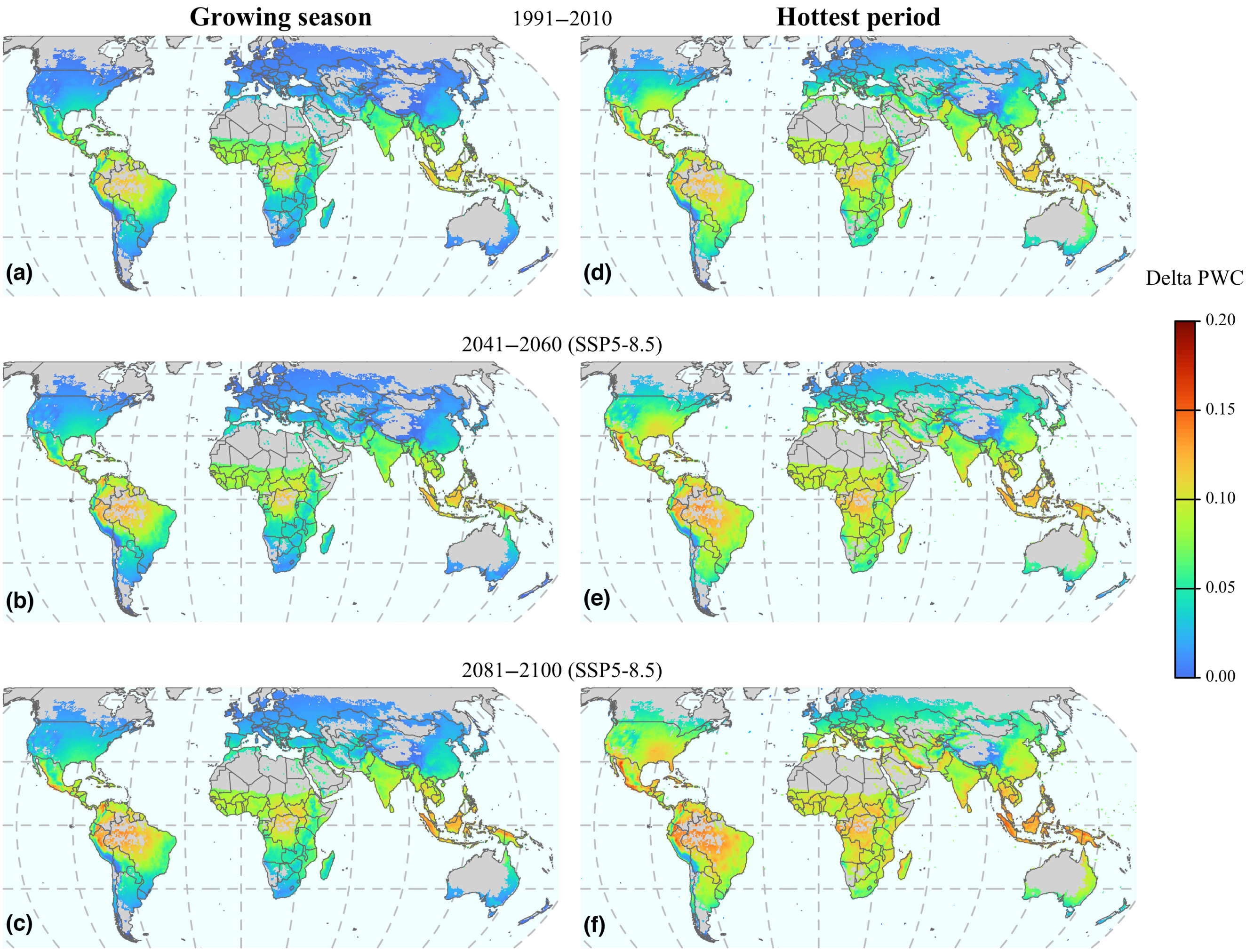

FIGURE 5 Impact of eliminating radiation in PWC values. Average improvement in PWCs during the crop growing season and the hottest period (the hottest 90 continuous days in the year) for three time periods: (a, d) recent past (1991–2010); (b, e) with mid-century (2041–2060) with SSP5-8.5; (c, f) end-century (2081–2100) with SSP5-8.5. Areas with no crops at the start of the 21st century are excluded (gray areas). Map lines delineate study areas and do not necessarily depict accepted national boundaries. PWC, Physical work capacity.

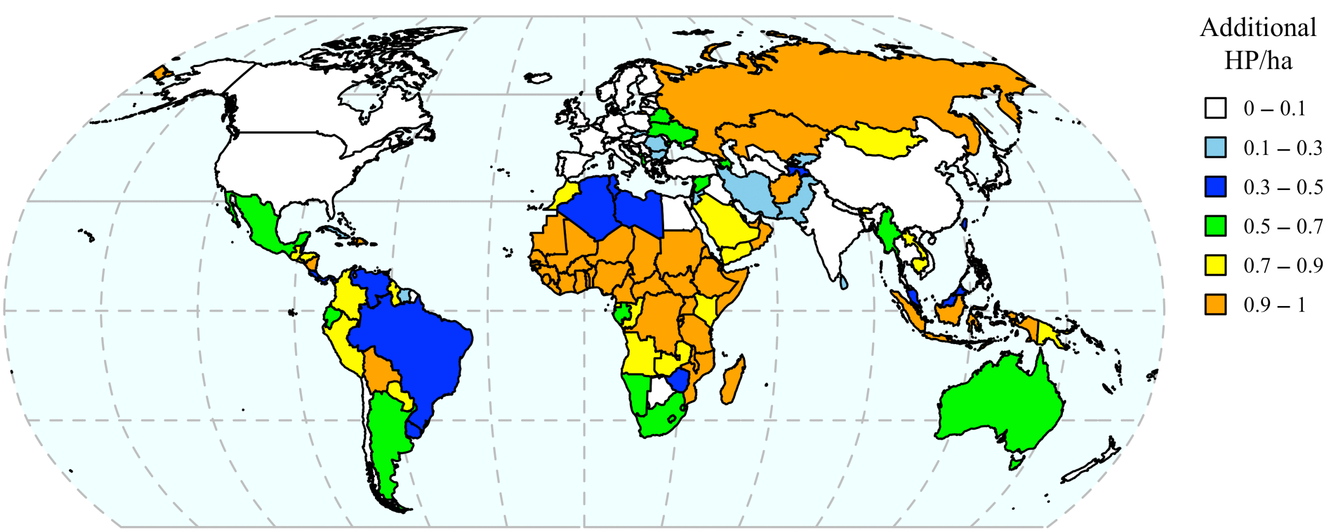

FIGURE 6 Additional mechanization (in horsepower, HP) needed to make 1 HP available *per hectare*, by country. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

To reduce the labor demands at the hottest times of year, there could be scope for shifting to varieties or crops with different growing periods that require less field labor or that have labor peaks in cooler parts of the year (Minoli et al., 2022). However, this shift depends on alternate cultivar or crop availability and profitability of the alternatives. The type of shift depends on the important climate conditions locally. Temperature is important in the temperate regions. In the tropics, cropping seasons are often determined by the rainy season period.

Agriculture field workers will likely need to adapt the way they work in the future (Ebi et al., 2021; Parsons et al., 2022). The nature of these changes will depend on the magnitude and types of climate changes. Safe work during periods within detrimental thermal conditions requires modifications, including increasing fluid consumption and moderating workloads with more frequent breaks (e.g., Sahu et al., 2013; Zander et al., 2015). Self-pacing lowers physical work capacity (Jay et al., 2019; Vanos et al., 2023) resulting in reduced productivity (Dasgupta et al., 2021; Graff Zivin & Neidell, 2014; Vanos et al., 2019; Yi & Chan, 2017; Zander et al., 2015). It might be possible to develop additional resilience through a greater heat acclimatization, characterized by lower absolute body temperatures at rest, greater sweating capacity, and an expanded blood plasma volume (Brown et al., 2022). Collectively, these adaptations may enable the maintenance of higher work output under some increases in heat stress without intolerable physiological heat strain. However, the extent to which these adaptations would continue to be effective under higher temperature, humidity, and extent of sun exposure is finite. Given the high heat and reduced PWC already present in some regions, it is possible that outdoor workers in these regions are already fully heat-acclimatized and therefore no further physiological adaptations are possible to provide additional protection. Hence, further technological, behavioral, and/or infrastructural adaptations are needed.

Potential heat stress mitigation strategies to extend safe working hours include the use of purposive shading near agricultural activities to reduce radiant heat load (Jay et al., 2021), which others (Dasgupta et al., 2021; Wolff et al., 2021) have shown to be a significant part of work capacity based on overall heat load. Such an approach would be beneficial for maintaining PWC in very hot (45°C) and dry (<20% relative humidity) climates, particularly for lightly clothed workers, but less so in high humidity conditions and heavily clothed workers (Foster, Smallcombe, Hodder, Jay, Flouris, Nybo, et al., 2022). Our simulation of reducing direct solar radiation to zero resulted in improvements of the PWC ratio of between 0.05 and 0.10 in the hottest periods and regions. These results are unlikely to be implemented in the field but selective shading might be beneficial for some crops as well as humans and livestock.

Other behavioral adaptation strategies include working more during the earliest hours of the day, including before sunrise, dousing the skin with water, irrespective of water temperature, to support additional evaporative heat loss, while reducing sweating requirements (Morris et al., 2019) and maintaining a lower skin temperature (Morris et al., 2020), which blunt reductions in PWC, especially in hot/dry climates. The provision of drinking water to replace body water lost through sweating is essential for preventing escalations in cardiovascular strain that directly cause reductions in PWC (Flouris et al., 2018; Piil et al., 2018). Given the expected declines in PWC across large swaths of the globe, these techniques will be essential for reducing heat illness and creating safer working situations. However, given the broader vulnerability issues connected to agricultural workers and heat, we must consider policies that address the interactions of heat vulnerability with cultures, values, ethics, identities, experiences, and knowledge systems of agricultural workers in their location of work, as well as their governance, finances, and capabilities (Intergovernmental Panel on Climate Change, 2023).

Mechanized work also decreases physical labor needs and can sometimes be done at night with lights as an additional way to escape the worst of the heat. Large declines in PWC values will provide incentives to mechanize. This will be especially true for regions (such as in the Sahel) where crop production needs to happen in a short rainy season, and it is not possible to delay work much to wait for a heat wave to end. However, where fields are small and in more mountainous areas, large tractors may not be practical. Two-wheel tractors are important in South Asia, but operating these is not light work (van Loon et al., 2020).

Our work does not include the potential for chronic harm to health from repeated exposure to stressful thermal conditions. Workers will naturally slow down to reduce metabolic heat production but may override this natural response to meet agricultural schedules with little flexibility, exposing themselves to a greater risk of hyperthermia/heat illness. Finally, it does not include the potential for chronic harm to health from repeated exposure to stressful thermal conditions.

Our analysis does not use the full range of potential future changes in agriculture such as changes in cropping patterns and migration. Instead, it uses recent agricultural activities and worker counts and asks how, where, and when potential future heat stress could seriously affect agricultural activities in the recent past. Declines in worker productivity due to higher temperatures will compound the challenges that climate change poses to agriculture. Declines in the ability to work could result in a large economic burden (e.g., Borg et al., 2021; Casanueva et al., 2020). de Lima et al. (2021) suggested that heat stress on agricultural workers could exacerbate the impacts of climate change on crop production. Future work could model the effect of heat stress on economic losses, under various exposure conditions, regions, and adaptation strategies.

5 | CONCLUSIONS

Climate change is a challenge to food security (Pörtner, Roberts, Poloczanska, et al., 2022). Declines in worker productivity due to higher temperatures will compound the challenges, resulting in the need for more workers, reduced output, and higher prices, putting further pressure on vulnerable populations.

The PWC metric facilitates a quantitative assessment of the potential loss of the capacity of workers to perform physical labor in indoor or outdoor settings because of heat exposure. Some global locations are already experiencing significant losses in PWC during periods when a large share of crops is grown. Parts of the Amazon region in Brazil, West and East Central Africa, much of South and Southeast Asia, and parts of eastern China already see growing season losses of PWC of 0.2 to 0.3. With the thermal conditions that would prevail at end-century with the SSP5-8.5 scenario, average PWC values in these regions decline by as much as an additional 0.3. Regions with minimal present-day heat stress impacts could experience significant losses, including the southeast United States, much of southern South America, large areas in Africa, and more northerly areas in China.

Without adaptation, labor output would be reduced in large parts of the world. Extended periods of exposure to high levels of heat stress, especially in low-income regions where access to cooling retreats can be limited, would have further debilitating effects.

Adaptation options depend on location and can include shifting work to cooler times of the day and year; lighter weight and more breathable clothing; more provision of shade and access to water for drinking and for wetting the body; and changing crop types to those that can grow in the cooler periods of the year. If the thermal stresses are not too great, additional workers can be used to compensate for lost capacity. But at some point, the limits to adaptation for labor would be reached, affecting agricultural production, even if crops and livestock could tolerate these extremes and mechanization will likely play an ever more important role.

AUTHOR CONTRIBUTIONS

Gerald C. Nelson: Conceptualization; data curation; formal analysis; project administration; software; supervision; writing – original draft; writing – review and editing. **Jennifer Vanos:** Conceptualization; investigation; methodology; writing – review and editing. **George Havenith:** Conceptualization; methodology; resources; writing – review and editing. **Ollie Jay:** Conceptualization; methodology; resources; validation; writing – review and editing. **Kristie L. Ebi:** Conceptualization; investigation; writing – review and editing. **Robert J. Hijmans:** Formal analysis; methodology; resources; software; validation; visualization; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

All authors report no conflict of interest.

DATA AVAILABILITY STATEMENT

The data and code that support the findings of this study are openly available in zenodo at https://zenodo.org/doi/10.5281/zenodo.10429708 and Github at https://github.com/GeraldCNelson/heatstress-GCB. Climate data from the ISIMIP project can be accessed at https://doi.org/10.48364/ISIMIP.842396.1. Country-level data on agricultural labor and machinery can be downloaded from the USDA/ERS website at https://www.ers.usda.gov/data-products/international-agricultural-productivity/.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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