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Review article

Occupational heat stress and economic burden: A review of global evidence

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ABSTRACT

Background: The adverse effects of heat on workers' health and work productivity are well documented. However, the resultant economic consequences and productivity loss are less understood. This review aims to summarize the retrospective and potential future economic burden of workplace heat exposure in the context of climate change.
Methods: Literature was searched from database inception to October 2020 using Embase, PubMed, and Scopus. Articles were limited to original human studies investigating costs from occupational heat stress in English.
Results: Twenty studies met criteria for inclusion. Eighteen studies estimated costs secondary to heat-induced labor productivity loss. Predicted global costs from lost worktime, in US$, were 280 billion in 1995, 311 billion in 2010 (≈0.5% of GDP), 2.4–2.5 trillion in 2030 (>1% of GDP) and up to 4.0% of GDP by 2100. Three studies estimated heat-related healthcare expenses from occupational injuries with averaged annual costs (US$) exceeding 1 million in Spain, 1 million in Guangzhou, China and 250,000 in Adelaide, Australia. Low- and middle-income countries and countries with warmer climates had greater losses as a proportion of GDP. Greater costs per worker were observed in outdoor industries, medium-sized businesses, amongst males, and workers aged 25–44 years.
Conclusions: The estimated global economic burden of occupational heat stress is substantial. Climate change adaptation and mitigation strategies should be implemented to likely minimize future costs. Further research exploring the relationship between occupational heat stress and related expenses from lost productivity, decreased work efficiency and healthcare, and costs stratified by demographic factors, is warranted.
Key messages. The estimated retrospective and future economic burden from occupational heat stress is large. Responding to climate change is crucial to minimize this burden. Analyzing heat-attributable occupational costs may guide the development of workplace heat management policies and practices as part of global warming strategies.

1. Introduction

Heat stress in humans is defined as heat exceeding the level that can be tolerated without physiological impairment (Kjellstrom et al., 2016). Some workers are susceptible to heat stress due to increased ambient temperatures and workplace heat exposure, potential metabolic heat production from physical work, and clothing or personal protective equipment that reduces heat convection and sweat evaporation (Hanna et al., 2011; Kjellstrom et al., 2016; Parsons, 2014). Two systematic reviews have associated high temperatures with an increased rate of occupational injuries (OIs) (Binazzi et al., 2019; Bonafede et al., 2016). These OIs include both occupational heat-induced illnesses (OHIs)

Abbreviations: OHI, Occupational heat-induced illness; OI, Occupational injury; $T_{average}$, Average air temperature; T_{max}, Maximum air temperature.

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ranging from heat rash to life-threatening heat stroke (Xiang et al., 2014a, 2015) and those not directly caused by heat such as bone fractures resulting from injuries sustained while working in the heat (Binazzi et al., 2019; McInnes et al., 2017; Otte Im Kampe et al., 2016; Varghese et al., 2018, 2019).

Occupational heat stress can burden the economy (Dell et al., 2008, 2014; Xiang et al., 2014b, 2014c) as illustrated in Fig. 1. Heat-induced dehydration can impair physical and mental performance; this can compromise occupational safety, predisposing to OIs, and reduce work efficiency (Chi et al., 2005; Murray, 2007; Xiang et al., 2014a). A meta-analysis estimated a decrease in work productivity by 30% in either indoor or outdoor industries during heat stress conditions with a 2.6% productivity decline for each degree above 24 °C wet bulb globe temperature (WBGT) (Flouris et al., 2018). Productivity loss can also be caused by [1] workplace policies that reduce worktime (or increase break time) during high temperatures for occupational safety (Kjellstrom, 2016); [2] sick leave from OIs due to heat (Milton et al., 2000); and [3] reduced workforce secondary to resignations from jobs

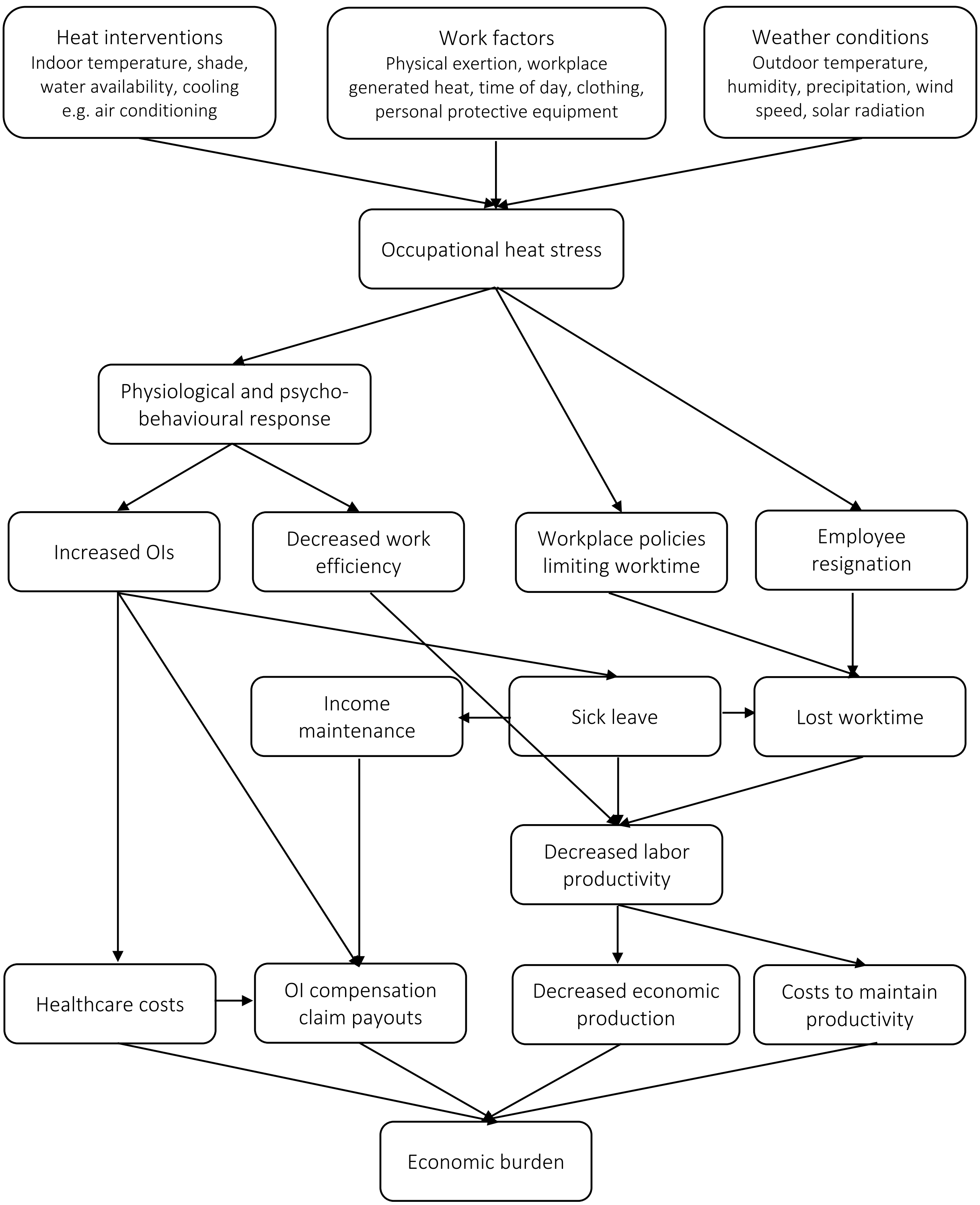

Fig. 1. Schematic illustration of economic burden related to occupational heat stress.

associated with high heat stress (Dunne et al., 2013; Heal and Park, 2016; Milton et al., 2000). Decreased labor productivity leads to less economic production and/or costs to maintain production such as overtime payments and replacement staff. Following OIs, additional expenses can arise from healthcare costs and income maintenance due to sick leave, which may be paid through injury compensation claims. As an example, studies in Adelaide, Australia, observed a 0.2% increase in daily OI compensation claims per 1 °C increase in daily maximum air temperature (T_{max}) below 37.7 °C (Xiang et al., 2014c); and a 6.2% increase in these claims during heatwaves (defined as ≥3 consecutive days with daily $T_{max} \geq 35$ °C) compared to non-heatwave periods (Xiang et al., 2014b). The same authors observed an even greater (12.7%) increase in claims for OHIs following a 1 °C increase in daily T_{max}; and 4–7 times during heatwaves compared to non-heatwave periods (Xiang et al., 2015).

Hot days are projected to increase in duration, frequency and intensity with global warming (Intergovernmental Panel on Climate Change, 2015). Worldwide average surface temperatures have increased by 0.85 °C (0.65 °C–1.06 °C) between 1880 and 2012 (Intergovernmental Panel on Climate Change, 2015). Projected changes are greatest in low- and middle-income countries and those with warmer climates (Kjellstrom et al., 2009b, 2016). This will affect labor productivity. There is extensive literature investigating the association between heat stress and decreased work-related productivity (Flouris et al., 2018; Levi et al., 2018), and labor productivity has been projected to decrease by up to 27% by the 2080s in Southeast Asia, the Caribbean, and Andean and Central America (Kjellstrom et al., 2009c).

To the best of our knowledge, the literature linking occupational heat stress to economic burden has yet to be comprehensively summarized. Although a literature review in 2019 identified ten studies that linked heat stress with increased healthcare costs from ambulance call-outs, emergency department visits and hospitalizations (Wondmagegn et al., 2019), it did not focus on costs associated with occupational heat stress. Day et al. (2019), Kjellstrom et al. (2016), and Orlov et al. (2019) discussed occupational costs from heat stress in the context of labor productivity loss but only briefly (Day et al., 2019; Kjellstrom et al., 2016; Orlov et al., 2019). This review aimed to summarize the literature investigating the associations between occupational heat stress and economic burden, encompassing costs of decreased productivity, and heat-related healthcare expenses from OIs. Both retrospective and potential future economic costs were reviewed.

2. Methods

2.1. Search strategy

A search strategy combining controlled vocabulary (MeSH, EMTREE) and keywords was created for PubMed, Embase and Scopus to identify peer-reviewed scientific journal articles (Appendix A). Search term protocols included three categories of search terms: "heat", "work", and either "medical costs" or "productivity", combined using the Boolean operator "AND" (Wee and Banister, 2016). Terms within each category, and the categories of "medical costs" and "productivity", were combined using the Boolean operator "OR." The wildcards "*" and "?" were used for particular keywords such as "labo*" to capture "labor," "laborer", "laborers", using American or British English spelling. Searches were not limited by year of publication. Potentially relevant articles identified by backward reference searching, including grey literature, were retrieved using Google Scholar.

2.2. Inclusion and exclusion criteria

The studies selected in this review met the following criteria:

- Written in English.
- Published from database inception to October 18, 2020.
- Limited to human populations.
- Publications with original research results on estimated costs secondary to occupational heat stress were included. Studies with results on costs without providing figures for total expenses, cost per capita, or costs as a proportion of economic output were excluded.
- Studies devoted solely to the effect of cold temperatures, without considering hot temperatures, were excluded.
- Studies devoted solely to non-occupational costs, without considering occupational costs separately, were excluded.
- Studies devoted solely to labor productivity loss without reference to associated costs were excluded.
- Conference abstracts, commentaries, editorials, and letters to the editor were excluded.
- Peer-reviewed articles without an abstract were excluded.

The search results were imported into an Endnote library. Relevant peer-reviewed studies were identified by a four-step process: [1] removing duplicates using the Endnote function of "find duplicates; " [2] screening titles; [3] reviewing abstracts of articles that were difficult to judge by screening their titles; and [4] reviewing the full-texts (Fig. 2).

All monetary figures were converted to United States Dollars (US$) as per previous reviews evaluating economic burden (Bahadori et al., 2009; Wondmagegn et al., 2019) using the exchange rate on September 14, 2019 from Google Finance (Reuters, 2019). The figure conversion for 1 US$ with the currencies for studies included in this review are shown in Appendix B.

3. Results

Twenty studies were included in the final review (15 peer-reviewed and five grey literature articles). These studies and their main cost estimates are summarized in Table 1 (retrospective results) and Table 2 (future estimates). One included study, Takakura et al. (2018), was a follow-up study to another included 2017 publication by the same authors using the same data. Studies were from China (n = 2), Australia (n = 2), Canada (n = 1), Germany (n = 1), India (n = 1), Italy (n = 1), Malaysia (n = 1), Spain (n = 1), USA (n = 1), multiple European cities or countries (n = 3), and global data across multiple continents (n = 6).

The metrics for estimating occupational heat exposure included WBGT (n = 12), T_{max} (n = 3), $T_{average}$ (average air temperature, n = 2), perceived temperature (n = 1), and heatwaves (n = 3), with two studies utilizing self-reported results without using a heat metric.

Thirteen studies estimated retrospective costs and ten estimated future costs, with three studies estimating both. Three studies investigated health-care costs, all retrospective and in relation to OIs. Eighteen studies investigated costs from heat-induced labor productivity loss including retrospective (n = 10) and future (n = 10) costs. The included mechanisms for estimating decreased productivity were assumed lost worktime from recommended work/rest ratios during heat stress (n = 8), reduced work efficiency estimated from exposure-response functions (n = 4), self-reported reduced work efficiency (n = 2), self-reported missed worktime (n = 2), costs related to maintaining production (n = 1), and long-term lost incomes following OIs (n = 1). Two studies assumed predefined estimates for the value of productivity loss.

3.1. Retrospective costs from heat stress

3.1.1. Costs associated with decreased labor productivity

Two studies estimated retrospective costs from worktime lost due to recommended altered work/rest ratios based on heat exposure. One study estimated retrospective global costs in 1995 to be $280 billion annually (Kjellstrom et al., 2019), and another estimated costs in 2010 to be $311 billion annually, ≈0.5% of global GDP (DARA, 2012). A manufacturing worksite in Ontario, Canada, with approximately 200 outdoor laborers, retrospectively estimated costs in summer from 2012 to 2018 (Vanos et al., 2019) and showed that approximately 1% of

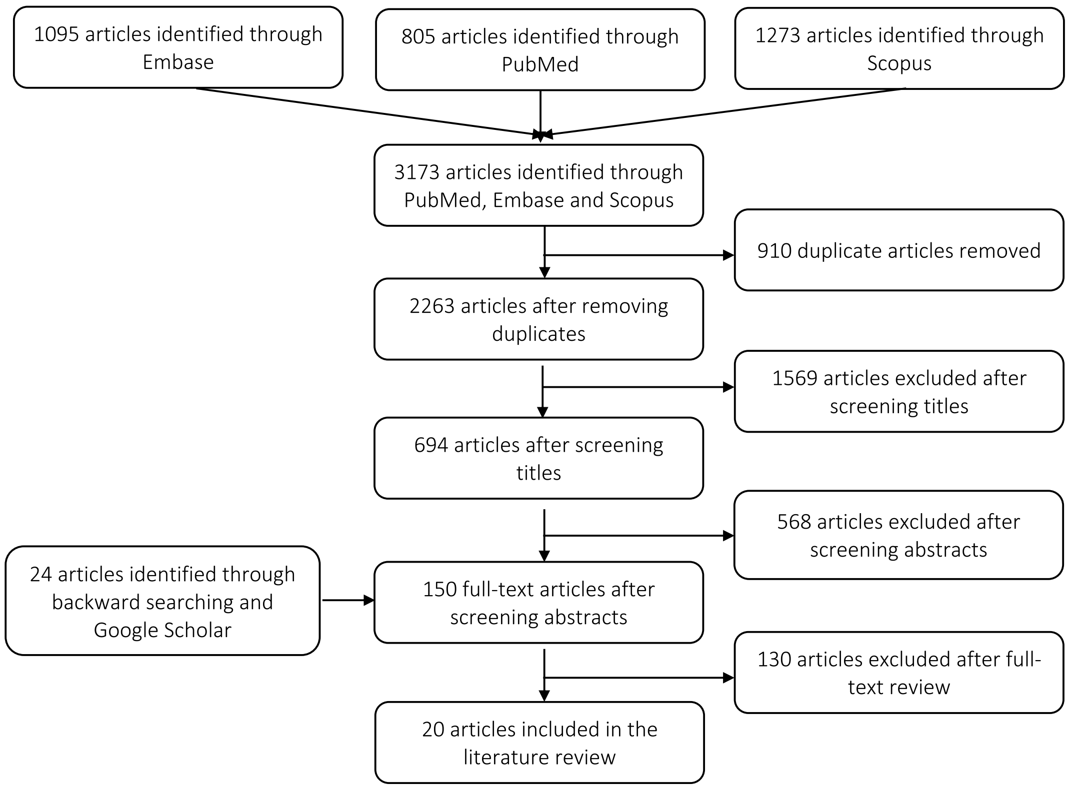

Fig. 2. Selection process for study inclusion.

annual work hours (21.8 h per worker), were lost annually, resulting in an average $827 annual loss per worker, totaling approximately $166, 316.

An exposure-response function was derived from the High Occupational Temperature Health and Productivity Suppression (Hothaps) program (Kjellstrom et al., 2009a), using data from previous epidemiological data sets (Sahu et al., 2013; Wyndham, 1969), to predict heat-induced work efficiency loss using WBGT and work intensity (Bröde et al., 2018; Kjellstrom et al., 2018). Using this function (hereafter: the Hothaps function), a wine and honey farm in Florence, Italy estimated hourly costs of $6.3 in 18 outside workers across the summers of 2017 and 2018, or $6667 in total (Morabito et al., 2020). The estimated costs across all wine workers in Florence (≈2500 workers) was $888,889. Using the same function, Orlov et al. (2019) estimated costs in agricultural and construction workers during the months of August 2003, July 2010, and July 2015 in 10 European countries (Austria, Croatia, Cyprus, France, Germany, Greece, Hungary, Italy, Spain, and Switzerland) (Orlov et al., 2019). Heatwaves occurred during these months, and these countries were estimated to have the largest heat-induced efficiency loss (Orlov et al., 2019). The mean costs per capita were $4.9 (August 2003), $3.7 (July 2010), and $4.4 (July 2015). Costs were approximately twice as large when estimated using ISO guidelines instead of an exposure-response function (Orlov et al., 2019). The costs estimated by Morabito et al. (2020) were also increased by a factor of 1.4 when using a similar exposure-response function based on ISO guidelines (Morabito et al., 2020).

A self-reported questionnaire survey from 2013 to 2014 estimated that 7% of Australia's workforce annually missed workdays due to heat at a cost equating to $845 per person ($58 per person across the Australian workforce) (Zander et al., 2015). Moreover, 70% of Australian workers reported reduced work efficiency from heat stress on at least one day yearly, costing $932 annually per person ($656 per person across the entire workforce). Another self-administered questionnaire survey from 2017 to 2018 estimated that 88% of Malaysia's urban workers had decreased work efficiency on at least one day annually (Zander and Mathew, 2019). Per worker, this was associated with a mean cost of $196 (SD: $434, median cost: $62). Considering the Malaysian workforce size in January 2018 of 14, 670, 500 (both urban and rural workers) (Mahidin, 2018), this likely represents a large economic burden to Malaysia. A questionnaire survey in Bhubaneswar and Sambalpur, two cities in Odisha, India, estimated lost wages from lost summer worktime during heatwave days compared to non-heatwave days for low-income urban outdoor workers in the informal sector (Das, 2015). The estimated annual cost was $7.7 per worker per heatwave day resulting from an average loss of 1.19 work hours. Applying this estimate to all the aforementioned workers in Odisha results in a loss of about $5 million. In the Australian, Malaysian, and Indian surveys, the causes of missed workdays and decreased efficiency, such as feeling unwell or work policy, were not investigated.

Martínez-Solanas et al. (2018) estimated costs associated with maintaining production and long-term lost incomes of $65.79 and $54.64 million, respectively, following an increase in OIs during high temperatures in Spain from 1994 to 2013 (Martínez-Solanas et al., 2018). This study based its cost estimates on a previous study estimating costs from OIs (Abiuso and Serra de La Figuera, 2008). Two studies estimated costs by assuming the percentage loss in productivity during heat stress. Decreased labor productivity during a 14-day heatwave in Nanjing, China, in 2013, caused an estimated economic cost of $3.88 billion, 3.43% of Nanjing's annual gross value of production (GVP) (Xia et al., 2018). This productivity loss comprised assumed worktime losses of 12% (indoor industries) and 75% (outdoor industries), and 250, 11.9, and 8.4 working days lost per heat-related death, hospital cardiovascular admission, and respiratory admission in 2013, respectively. Hübler et al. (2008) estimated costs of heat-induced labor productivity loss in Germany (2004) using predefined loss values of 3% and 12% from Bux (2006) (Hübler et al., 2008). With losses of 3% and 12%, the costs were $600 million (0.03% of GDP) and $2.7 billion (0.11% of GDP), respectively.

Table 1
Overview of studies estimating retrospective economics costs from occupational heat stress. All monetary figures were converted to United States Dollars using the exchange rate on September 14, 2019.

Study	Location	Time period	Study design	Heat and cost metrics	Statistical analysis	Main cost estimates
DARA 2012 (DARA, 2012). Grey literature	Global: 192 countries	2010	Ecological	*Heat:* WBGT (°C) *Cost:* GDP from labor productivity loss, estimated by lost hourly worktime	Global/sub-regional scale model to project labor productivity loss, estimated based on ISO and NIOSH WBGT thresholds.	\$314 billion annually, ≈0.5% of global GDP. GDP cost per country was more significant in low- and middle-income countries and those with warmer climates.
Das, 2015 (Das, 2015)	Bhubaneswar and Sambalpur, Odisha, India	25th April – May 20, 2013	Prospective cohort questionnaire	*Heat:* Heatwave days based on T_{max} *Cost:* Income lost from worktime lost in summer during heatwvave days compared to non-heatwave days	Costs were estimate using lost worktime obtained from survey responses multiplied by average hourly income. Only low-income urban outdoor workers in the informal sector were used for analysis.	\$7.77 annually per worker during heatwaves, 0.12% of their annual income. Applying this estimate to all 644,000 low-income urban outdoor workers in Odisha's informal sector gives combined cost of \$5 million.
Hübler et al., 2008 (Hübler et al., 2008)	Germany	2004	Ecological	*Heat:* perceived temperature (°C) *Cost:* GDP from labor productivity loss, assumed as 3% or 12% loss on days with perceived temperature $\geq 32°$	Macroeconomic model using GDP in 2004, number of days where perceived temperature $\geq 32°$ and associated labor productivity loss.	\$600 million (0.03% of GDP) or \$2.7 billion (11% of GDP) with labor productivity loss of 3% and 12%, respectively.
Kjellstrom et al., 2019 (Kjellstrom et al., 2019). Grey literature	Global	1981–2010	Ecological	*Heat: WBGT (°C)* *Cost:* GDP from labor productivity loss, estimated by decreased work efficiency	Hothaps exposure-response function to estimate worker efficiency loss based on WBGT. Loss measured as the number of full-time jobs lost is multiplied by GDP earned by worker.	\$280 billion annually. GDP cost per country was more significant in low- and lower-middle-income countries and those with warmer climates.
Ma et al., 2019 (Ma et al., 2019)	Guangzhou, China	2011–2012	Ecological	*Heat:* WBGT (°C) *Cost:* Insurance payouts from OI claims attributable to days where WBGT > 25 °C	Daily time-series analysis using quasi-Poisson regression with distributed lag non-linear model.	\$1.63 million during time period. On days where WBGT >25 °C, OI insurance payouts increased by 4.1% (95% CI: 0.2–7.7%).
Martínez-Solanas et al., 2018 (Martínez-Solanas et al., 2018)	Spain	1994–2013	Ecological	*Heat:* T_{max} (°C) *Costs:* Cost from heat-attributable OIs with at least one day of sick leave, divided into health costs, labor productivity loss (maintaining production and long-term lost incomes), and costs of pain and suffering	Distributed lag nonlinear models for association between daily T_{max} and number of daily OIs, with pooled estimates from multivariable meta-regression.	\$354.88 million annually. Costs from pain and suffering: \$203.30, maintaining production: \$65.79, long-term lost incomes: \$54.64, and health costs: \$31.18.
Morabito et al., 2020 (Morabito et al., 2020)	Wine and honey farm in Florence, Italy	Summer 2017 and 2018	Retrospective cohort	*Heat: WBGT (°C)* *Cost:* GDP from labor productivity loss, estimated by hourly decreased work efficiency.	Exposure-response functions (Hothaps and ISO) to estimate heat-induced worker efficiency loss based on WBGT. Loss is the product of productivity loss (%) and workers' salaries. 18 workers	\$6.3 hourly per worker (\$6667 total) using Hothaps function, equal to \$888,889 in total across all wine workers (≈2500) in Florence. Costs increased by ~ 1.4 when using the ISO function.
Orlov et al., 2019 (Orlov et al., 2019)	10 European countries	August 2003, July 2010, and July 2015	Ecological	*Heat: WBGT (°C)* *Cost:* GDP from labor productivity loss, estimated by hourly decreased work efficiency.	Hothaps exposure-response function to estimate worker efficiency loss based on WBGT. Loss inputted in computable general equilibrium model to estimate cost for outdoor (agricultural and construction) workers.	Mean per capita costs of \$4.9 (August 2003), \$3.7 (July 2010), and \$4.4 (July 2015). Equivalent to \$120 + \$61 (August 2003), \$84 + \$41 (July 2010) and \$132 + \$72 per agricultural + construction worker. Costs were approximately doubled when estimated using ISO guidelines instead of the Hothaps function.
Vanos et al., 2019 (Vanos et al., 2019)	Manufacturing workplace in Ontario, Canada	2012–2018	Retrospective cohort	*Heat:* WBGT (°C) *Cost:* GDP from productivity loss in outdoor laborers, estimated by lost hourly worktime per summer	Estimated worktime lost based on ACGIH WBGT thresholds and associated hourly wages. ≈200 workers	\$166,316 total, based on 21.8 h lost per worker annually (≈1% of annual work hours). Cost of \$827 per worker.
Xia et al., 2018 (Xia et al., 2018)	Nanjing, China	5th – August 18, 2013	Ecological	*Heat:* Heatwave based on T_{max} and $T_{average}$ (°C) *Cost:* GVP from labor productivity loss during a heatwave, estimated by lost worktime	Supply-driven IO model derived from a traditional Leontief IO model. Working time loss of 12% and 75% assumed for indoor and outdoor industries,	\$3.88 billion, 3.43% of Nanjing's GVP in 2013. Most costs were indirect. Economic loss per industry: manufacturing: 63.1%, service: 14.3%, construction:

(*continued on next page*)

Table 1 (*continued*)

Study	Location	Time period	Study design	Heat and cost metrics	Statistical analysis	Main cost estimates
					respectively. Additionally, each heat-related death, cardiovascular hospital admission and respiratory hospital admission was treated as 250, 11.9 and 8.4 working days lost, respectively.	10.7%, agriculture: 7.6%, energy supply: 3.3%, mining: 0.9%.
Xiang et al., 2018 (Xiang et al., 2018)	Adelaide, Australia	2000–2014	Ecological	*Heat:* T_{max} (°C) and heatwave periods based on T_{max} *Cost:* Daily compensation claims for OHIs. Claim amounts were given based on number of lost workdays and employee medical expenditure	Daily time series model with restricted cubic splines models to estimate crude associations between T_{max} and costs. Linear regression to estimate association between heat and log-transformed costs.	$4,139,890 for all OHI claims from 2000 to 2014. Average cost of $9452 per OHI claim. A 1 °C increase in T_{max} above 32.9 °C was associated with a 41.6% increase (95% CI: 29.3%–55.1%) in medical costs.
Zander et al., 2015 (Zander et al., 2015)	Australia	2013–2014	Prospective cohort questionnaire	*Heat:* N/A *Cost:* Lost income from decreased labor productivity yearly, estimated as the sum of missed workdays and reduced work efficiency	Non-parametric Kruskal-Wallis tests and multiple comparison tests. Workers reported their incomes and perceived productivity loss from heat stress on an online survey. 1726 survey respondents.	$6.2 (95% CI: 5.2–7.3) billion, 0.33%–0.47% of Australia's GDP, equal to $655 per worker. This included costs of $58 and $656 per person from missed workdays and reduced work efficiency, respectively, with some money saved from workers carrying out additional compensatory work.
Zander and Mathew, 2019 (Zander and Mathew, 2019)	Urban Malaysia	2017–2018	Prospective cohort questionnaire	*Heat:* N/A *Cost:* Lost income from decreased work efficiency yearly	Non-parametric Kruskal-Wallis tests and multiple comparison tests. Workers reported their incomes and perceived productivity loss from heat stress on an online survey. 514 survey respondents.	$196 mean cost per worker (SD: $434), and $62 median cost per worker (9.5% of median annual income).

Acronyms; ACGIH: American Conference of Governmental Industrial Hygienists, CI: confidence interval, GDP: gross domestic product, GVP: gross value of production, Hothaps; High Occupational Temperatures Health and Productivity Suppression; IO: industrial-total output, ISO: International Organization for Standardization, NIOSH: National Institute for Occupational Safety and Health, OHI: occupational heat-induced illness, OI: occupational injury, $T_{average}$: average air temperature, T_{max}: maximum air temperature, WBGT: wet bulb global temperature.

3.1.2. *Healthcare costs from OIs*

Three studies estimated healthcare costs from heat stress: all in relation to OIs. Two estimated daily OI claims and payouts – one investigated all OIs (Ma et al., 2019), and the other only included OHIs (Xiang et al., 2018). In metropolitan Adelaide, Australia, from 2000 to 2014, there were 438 OHI claims (Xiang et al., 2018). These resulted in costs of $4,139,890, equivalent to $9452 per claim. The authors observed a J-shaped curve relationship between daily T_{max} and OHI insurance claim costs (Xiang et al., 2018). Above a threshold of 32.9 °C, a 1 °C increase in daily T_{max} was associated with a 41.6% increase in costs (95% CI, 29.3%–55.1%). Xiang et al. (2018) observed no statistically significant differences for cost per claim between heatwave and non-heatwave periods ($7978 vs $8606, respectively, P-value = 0.14). This study excluded costs from OIs that were not OHIs, omitting OIs that could potentially have been caused by heat (Otte Im Kampe et al., 2016; Spector et al., 2019). In Guangzhou, China from 2011 to 2012, when WBGT exceeded 25 °C, OI insurance payouts increased by 4.1% (95% CI: 0.2–7.7%) and the number of OI claims increased by 4.8% (95% CI: 2.9–6.9%) (Ma et al., 2019). This represented $1.63 million in total. Martínez-Solanas et al. (2018) estimated heat-related health costs of $31.18 million from treatment and rehabilitation for OIs in Spain from 1994 to 2013 (Martínez-Solanas et al., 2018). This study also estimated expenses of $203.3 million from pain and suffering (level of disability). The components for expenses of pain and suffering were not specified, but typically these can include additional health costs such as medications and disability-specific aids (Mitra et al., 2017).

3.2. *Projected future costs from labor productivity loss*

The ten studies that projected future costs from occupational heat stress estimated labor productivity loss using recommended work/rest ratios, except for Kjellstrom et al. (2019) and Orlov et al. (2020) who estimated decreased work efficiency instead (Kjellstrom et al., 2019; Orlov et al., 2020), and Hübler et al. (2008) who assumed the value of productivity loss during heat stress (Hübler et al., 2008). Eight studies projected costs using future climate scenarios with high greenhouse gas concentration scenarios. These scenarios, from highest to lowest concentrations, were RCP8.5, SRES A2, and SRES A1B (Intergovernmental Panel on Climate Change, 2007a; Intergovernmental Panel on Climate Change, 2007b; Intergovernmental Panel on Climate Change, 2015) with RCP8.5 representing no climate mitigation. Five studies compared costs under one of these scenarios to those under either the RCP2.6, SRES 1 B or ENSEMBLES E1 scenario, scenarios with lower predicted greenhouse gas concentrations due to higher levels of climate mitigation (Intergovernmental Panel on Climate Change, 2007a; Intergovernmental Panel on Climate Change, 2007b; Intergovernmental Panel on Climate Change, 2015; Kjellstrom et al., 2019; Orlov et al., 2020; van der Linden and Mitchell, 2009). Takakura et al. (2017 and 2018) and Orlov et al. (2020) also projected shared socioeconomic pathways (SSPs), where each of the five SSPs pose different challenges for climate mitigation and adaptation (O'Neill et al., 2013; Van Vuuren and Carter, 2014). These projected climate and socioeconomic scenarios are described in Appendix C.

Table 2
Overview of the ten (ecological) studies estimating projected future economics costs from occupational heat stress.

Study	Location	Time period	Heat and cost metrics	Projection scenarios	Statistical analysis	Main cost estimates
Costa and Floater 2015 (Costa and Floater, 2020). Grey literature	Antwerp, Bilbao and London	2081–2100	*Heat:* WBGT (°C) *Cost:* Annual GVA from labor productivity loss, estimated by lost hourly worktime	*Climate:* RCP8.5	Constant elasticity of substitution production functions per industrial sector using hourly productivity loss, estimated with ISO WBGT thresholds. Calculated annual lost for year in time period with maximal productivity loss.	Annual GVA loss of 0.4% in London ($2111 million), 2.1% in Antwerp ($2778 million) and 9.5% in Bilbao ($777 million). GVA was observed to monotonically decrease with increasing WBGT.
DARA 2012 (DARA, 2012) Grey literature	Global: 192 countries	2030	*Heat:* WBGT (°C). *Cost:* GDP from labor productivity loss, estimated by lost hourly worktime	*Climate and socioeconomic:* SRES A2	Global/sub-regional scale model to project labor productivity loss, estimated based on ISO and NIOSH WBGT thresholds, using 2010 as the baseline year.	$2.5 trillion annually, ≈1.2% of GDP. This compromised the majority of costs secondary to climate change in 2030 (2.1% of GDP). GDP loss (%) was larger in low- and middle-income countries and those with warmer climates.
Hsiang et al., 2014 (Hsiang et al., 2020). Grey literature	USA	2020–2099	*Heat:* T_{max} (°C) *Cost:* GDP from labor productivity loss, estimated by lost worktime	*Climate:* RCP8.5	Integrated assessment model using labor productivity loss, estimated using regression equations with variables for environmental factors, occupational activities, day of the week, seasonal occupational trends and US county.	Projected costs ranged from $0.1 to $22 billion in 2020–2039, $10 to $52 billion on 2040–2059, and $42 to $150 billion from 2080 to 2099 (0.3%–0.9% of GDP) annually.
Hübler et al., 2008 (Hübler et al., 2008)	Germany	2071–2100	*Heat:* perceived temperature (°C) *Cost:* GDP from assumed labor productivity loss of 3% or 12% on days with perceived temperature ≥ 32°	*Climate and socioeconomic:* SRES A1B and B1	Macroeconomic model using GDP and wage share in 2004, number of days where perceived temperature ≥ 32° and associated labor productivity loss.	Under SRES A1B, almost $2.2 billion with 3% productivity loss and almost $8.9 billion with 12% productivity loss annually. Under SRES B1 with 12% productivity loss, cost decreases from almost $8.9 billion to $4.7 billion annually.
Kjellstorm et al., 2019 (Kjellstrom et al., 2019). Grey literature	Global	2011–2040	*Heat: WBGT (°C)* *Cost:* GDP from labor productivity loss, estimated by decreased work efficiency	*Climate:* RCP2.6 *Socioeconomic:* National industrial-specific estimates of employment-to-population ratio	Hothaps exposure-response function to estimate worker efficiency loss based on WBGT. Cost estimated from estimated loss multiplied by GDP earned by worker.	$2.4 trillion annually. GDP cost per country was larger in low- and lower-middle-income countries and those with warmer climates. Costs estimated under RCP6.0, though not reported, were stated to be similar to those under RCP2.6 since projected temperatures only differed after 2030.
Kovats et al., 2011 (Kovats et al., 2011). Grey literature	Europe	2011–2100	*Heat:* WBGT (°C) *Cost:* GDP from labor productivity loss, estimated by lost hourly worktime	*Climate and socioeconomic:* SRES A1B and E1	Global/sub-regional scale model to project labor productivity loss, estimated based on ISO and NIOSH WBGT thresholds. Costs calculated using productivity loss, GDP/capita and baseline labor distributions across agriculture, industry and services sectors for each country.	Under SRES A1B, $41 – $84 million in 2020s, $132 – $359 million in 2050s, and $330 to $826 million in 2080s annually. Under E1 scenario, yearly costs increased to $61 - $123 in 2020s, and reduced to $68 - $159 million in 2050s and $68 - $161 million in 2080s.
Orlov et al., 2020 (Orlov et al., 2020)	Global	2011–2100	*Heat: WBGT (°C)* *Cost:* GDP from labor productivity loss, estimated by decreased work efficiency	*Climate and socioeconomic:* RCP2.6 with combined SSP1 and SSP4 scenario, and RCP8.5 with SSP5	Hothaps exposure-response function to estimate worker efficiency loss based on WBGT. Loss inputted in computable general equilibrium model to estimate cost. Air-conditioning and mechanization were assumed for indoor and outdoor industries, respectively.	Under RCP2.6, GDP loss of 0.5% by 2050 and 2100. Under RCP8.5, GDP losses of 0.7% by 2050 and 1.4% by 2100, or 0.7% and 1.8% without the assumption of mechanization, respectively. The non-mechanization 2100 costs estimated by ISO guidelines instead of the Hothaps function were 0.9% (RCP2.6) and 2.4% (RCP8.5).
Roson et al., 2016 (Roson and Sartori, 2016)	Global	N/A	*Heat:* WBGT (°C) *Cost:* GDP from labor productivity loss, estimated by lost hourly worktime	*Climate:* 3 °C increase in monthly average WBGT	Assumed linear labor productivity losses when WBGT >26 °C, >28 °C and >30° for agricultural, manufacturing and service sectors, respectively, with minimum productivity of 25%. Estimated cost was product of productivity loss and sectoral share of labor income.	With 3 °C increase in WBGT, mean GDP cost of 0.1779% per country, larger in low- and middle-income countries and those with warmer climates.
Takakura et al., 2017 (Takakura et al., 2017)	Global	2100	*Heat:* WBGT and $T_{average}$ (°C) *Cost:* GDP from labor productivity loss,	*Climate:* RCP2.6, RCP4.5, RCP6.5 and RCP8.5	Asia-Pacific integrated model/computable general equilibrium model with variables for air-conditioning device use, future	GDP losses were 2.8%, 2.6% and 4.0% with RCP8.5, and 0.48%, 0.46% and 0.49% with RCP2.6, under SSP1, SSP2 and SSP3,

(*continued on next page*)

Table 2 (*continued*)

Study	Location	Time period	Heat and cost metrics	Projection scenarios	Statistical analysis	Main cost estimates
			estimated by lost hourly worktime, compared to 2005	*Socioeconomic:* SSP1, SSP2 and SSP3	climate and socioeconomic projections, and future worktime reduction based on future ISO and NIOSH WBGT thresholds.	respectively. Each 1 °C increase in $T_{average}$ associated with losses of 0.63%, 0.58% and 0.93% under the aforementioned SSPs, respectively.
Takakura et al., 2018 (Takakura et al., 2018)	Global	2090s	*Heat:* WBGT and $T_{average}$ (°C) *Cost:* GDP from labor productivity loss, estimated by lost hourly worktime, compared to 2005	*Climate:* RCP2.6, RCP4.5, RCP6.5 and RCP8.5 *Socioeconomic:* SSP2	As per Takakura et al., 2017, but with a small modification to better describe the diurnal variation of WBGT.	GDP losses were 2.8% (1.7–3.8%) and 0.44% (0.41–0.92%) under RCP8.5 and RCP2.6, respectively. With work shifts up to 3 h earlier in day, losses decreased to 1.6% (1.0–2.4%) and 0.14% (0.12–0.47%), respectively. Losses of 0.48%, 0.68%, 1.2% and 1.7% with increases in $T_{average}$ by 1.5 °C, 2.0 °C, 3.0 °C and 4.0 °C, respectively.

All monetary figures were converted to United States Dollars using the exchange rate on September 14, 2019. Acronyms; GDP: gross domestic product, GVA: gross value added, Hothaps; High Occupational Temperatures Health and Productivity Suppression; ISO: International Organization for Standardization, RCP: representative concentration pathway, SRES: Special Report on Emissions Scenarios, $T_{average}$: average air temperature, T_{max}: mean air temperature, WBGT: wet bulb global temperature.

3.2.1. *Projected global costs*

Four studies projected heat-related workplace costs globally. Both Kjellstrom et al. (2019) and the international organization "DARA" estimated an annual global cost of $2.4–2.5 trillion in 2030 (under RCP2.6 and SRES A2, respectively), ≈1.2% of GDP (DARA, 2012; Kjellstrom et al., 2019). This is a large increase over DARA's baseline 2010 cost estimate of $311 billion annually. Kjellstrom et al. (2019) estimated similar costs in 2030 using RCP6.0 instead of RCP2.6, noting that temperatures under both RCPs only notably differed after 2030. Takakura et al. (2017) projected global GDP losses by 2100 were approximately 5.5–8 times larger under RCP8.5 compared to RCP2.6 (Takakura et al., 2017). Under SSP1, SSP2 and SSP3, these estimated losses under RCP8.5 were 2.84%, 2.62%, and 3.96%, respectively, and under RCP2.6 were 0.48%, 0.46%, and 0.49%, respectively (Takakura et al., 2017). The results were similar in the authors' subsequent 2018 study using the SSP2 scenario, with a model improvement to better estimate the diurnal variation of WBGT (Takakura et al., 2018). Orlov et al. (2020) projected global GDP losses of 0.5% by 2050 and 2100 under RCP2.6 and a combined SSP1 and SSP4 scenario, and 0.7% (1.4%) by 2050 (2100) under RCP8.5 and SSP5 (Orlov et al., 2020). Roson et al. projected that a 3 °C increase in WBGT and its associated labor productivity decrease in the agriculture, manufacturing and services sectors would collectively cause a mean GDP cost of 0.18% globally (Roson and Sartori, 2016). This study did not project socioeconomic or other weather variables.

Three studies projected relationships between global temperature increases and costs. Takakura et al. (2017) projected an approximately linear relationship between global $T_{average}$ rises and GDP loss based on decreased work-rest ratios from WBGT thresholds (Takakura et al., 2017). For each 1 °C increase in global $T_{average}$, GDP losses of 0.63%, 0.58%, and 0.93% were estimated under SSP1, SSP2, and SSP3 scenarios, respectively. However, the same authors in their subsequent study observed a curvilinear instead of a linear relationship, with progressive increases in GDP following incremental increases in global $T_{average}$ (Takakura et al., 2018). Based on this relationship, under SSP2, global $T_{average}$ increases of 1.5 °C, 2.0 °C, 3.0 °C, and 4.0 °C would decrease GDP in 2090 by 0.48%, 0.68%, 1.2%, and 1.7%, respectively (Takakura et al., 2018). Costa and Floater (2015) observed a non-linear (monotonically decreasing) relationship with WBGT and gross value added (GVA, the economic value of produced goods and services minus intermediate consumption) (Costa and Floater, 2020).

3.2.2. *Projected costs according to region*

In the USA, Hsiang et al. (2014) projected annual, direct costs for labor productivity loss with 67% confidence intervals (Hsiang et al., 2020). Under RCP8.5, these costs ranged from $0.1 to $22 billion from 2020 to 2039, $10 to $52 billion from 2040 to 2059, and $42 to $150 billion from 2080 to 2099 (0.3%–0.9% of GDP). In Germany, by 2071–2100 under SRES A1B, labor productivity losses of 3% and 12% would lead to estimated annual costs of almost $2.2 billion and $8.9 billion, respectively (Hübler et al., 2008). Under SRES B1 and a productivity loss of 12%, the cost in 2071–2100 would decrease from almost $8.9 to $4.7 billion.

Costa and Floater (2015) projected, in the hottest year in the period 2081–2100 under RCP8.5, a GVA loss of 0.4% in London ($2111 million), 2.1% in Antwerp ($777 million), and 9.5% in Bilbao ($2778 million) (Costa and Floater, 2020). The authors reasoned that the percentage loss of GVA was less in London compared to Antwerp and Bilbao because of a colder climate and a larger proportion of service workers; the service sector is associated with decreased occupational heat exposure and labor intensity compared to other sectors (Costa and Floater, 2020). Kovats et al. (2011) estimated projected costs from reduced worktime in Europe to be $41 – $84 million in the 2020s, $132 – $359 million in the 2050s, and $330 – $826 million in the 2080s under the SRES A1B scenario (Kovats et al., 2011). Under the E1 scenario, these costs increased to $61 – $123 million in the 2020s and reduced to $68 – $159 million in the 2050s and $68 – $161 million in the 2080s. The costs in the 2080s were approximately five times larger under SRES A1B than under ENSEMBLES E1. Lower values within these cost range reflect lower projected agriculture-to-service worker ratios compared to the ratio in 2000, with the highest limit representing no change in the ratio. Decreased costs were projected in Northern and Western Europe compared to Southern and Eastern Europe. This was also concluded to be because of a colder climate and a higher workforce proportion of service workers in Northern and Western Europe (Kovats et al., 2011).

Estimated costs as a proportion of GDP were larger in low- and middle-income countries and regions with warmer climates (DARA, 2012; Kjellstrom et al., 2019; Orlov et al., 2020; Roson and Sartori, 2016; Takakura et al., 2017). DARA estimated that in these areas, such as West and Central Africa, GDP loss due to occupational heat stress may be up to 6% instead of a global approximate 1.2% loss (DARA, 2012). Similarly, Kjellstrom et al. (2019) estimated GDP losses of 1.5% and 4.0% in low- and lower-middle-income countries, respectively, 2.3% in Asia and the Pacific and 1.8% in Africa (Kjellstrom et al., 2019). Roson et al. (2016), following an increase in global $T_{average}$ by 3 °C, estimated the highest GDP losses in West Africa including Nigeria (8.21%), Ghana, (7.61%), Cote d'Ivoire (7.35%) and Togo (6.79%), followed by Southeast Asia (6.47%). Takakura et al. (2017) observed the highest GDP loss rates in India and South-East Asia (14.3%–17.3% and 4.6%–6.9% under RCP8.5, respectively, with the ranges reflecting different SSPs) (Takakura et al., 2017). Sub-Saharan Africa and other Asian regions had high GDP loss rates similar to South-East Asia only under SSP3, indicating higher sensitivity to future socioeconomic conditions. Similar results were estimated globally under SSP2 in the authors' subsequent study but with stratification of countries into five regions instead of at the individual country level; a higher proportion of costs occurred in Asia, Middle East and Africa (Takakura et al., 2018). By 2100 under RCP8.5, Orlov et al. (2020) estimated GDP losses of 6%, 3.6%, and 2.4% in South Asia, Africa, and South-East Asia, respectively (Orlov et al., 2020). In comparison, these authors observed less than 1% losses in Europe, North America, and Oceania.

3.3. Averted costs under climate adaptation measures

Morabito et al. (2020) and Orlov et al. (2019) estimated the change in retrospective costs by working in the shade instead of the sun (Morabito et al., 2020; Orlov et al., 2019). The two studies estimated that under the shade, costs decreased by factors of over 6 and 10, respectively. Morabito et al. (2020) also estimated that shifting work schedules 2 h earlier (from 8am-5pm to 6am-3pm) reduced costs by about 33% (Morabito et al., 2020). Orlov et al. (2019) observed that direct costs from agriculture can be reduced by nearly 66% by working overtime to produce the same quantity of goods and services compared to working normal hours without heat stress (Orlov et al., 2019).

Three studies estimated the effect of climate adaptation measures on projected future costs. Costa and Floater (2015) evaluated five adaptation measures in reducing the projected annual cost of $777 million in Antwerp from 2081 to 2099 in indoor industrial sectors. These measures were: air conditioning access, solar blinds, increased indoor ventilation, adapting working hours to avoid work from 11am to 5pm, and increased insulation through glazing. The averted costs in millions were $713, $549, $517, $173, and -$127, respectively, with the negative $127 million figure representing an additional expense (Costa and Floater, 2020). Air conditioning was potentially the most effective adaptation, and only a small proportion of costs were averted with modified work hours. In another study, Takakura et al. (2018) estimated the global effect of shifting outdoor work to start and end 3 h earlier to reduce occupational heat exposure. With this measure, projected GDP losses reduced from 2.8% (1.7%–3.8%) to 1.6% (1.0%–2.4%) under RCP8.5 and from 0.44% (0.41%–0.92%) to 0.14% (0.12–0.47%) under RCP2.6, with the ranges reflecting costs from different projection models (Takakura et al., 2018). Shifting hours earlier was generally more effective in countries that were not OECD90 countries (i.e. lower-income countries) (Takakura et al., 2018). Orlov et al. (2020) estimated GDP losses when assuming mechanization for outdoor industries (agriculture and construction), with increased mechanization occurring with economic growth (Orlov et al., 2020). The estimated losses without mechanization compared to their mechanization counterparts were similar in 2050 and in 2100 were $<$0.1% greater under RCP2.6 (total loss of 0.5%) and $\approx$0.4% under RCP8.5 (total loss of 1.8% loss instead of 1.4% loss). The 2100 costs without mechanization were also estimated using ISO guidelines instead of the Hothaps exposure-response function, giving larger GDP losses of 0.9% and 2.4%.

3.4. Costs per industry

Takakura et al. (2017), Xiang et al. (2018), and Costa and Floater (2015) investigated direct costs from heat. Xiang et al. (2018) identified that the cost per claim in South Australia from 2000 to 2014 was considerably greater in the mining sector compared to other industries ($74,963 per claim; the next highest cost was from transport and storage at $14,997 per claim) (Xiang et al., 2018). The authors observed more than thrice the overall costs from OHI claims in the mining (and community services) sectors compared to other sectors. Costa and Floater (2015) projected higher proportions of losses in the construction and manufacturing sectors in Antwerp, Bilbao, and London, from 2081 to 2100, relative to the fractions of their baseline sectors' GVA, though the authors did not provide exact cost figures (Costa and Floater, 2020).

Takakura et al. (2017) projected greater costs in outdoor sectors (the construction followed by the primary industry sectors) (Takakura et al., 2017). These sectors had assumed greater work intensities than the indoor sectors (manufacturing and services) and thus more lost worktime. The indoor sectors were only projected to have decreased labor productivity under SSP3, where low economic-growth limited access to air conditioning. Similar results were estimated under SSP2 in the authors' subsequent study using the same industrial sectors (Takakura et al., 2018). This study projected GDP costs per industry by grouping countries into five regions. The OECD90 region was associated with lower and higher proportions of projected costs in the primary industry sector and construction sector, respectively. The inverse was true for the LAM (Latina America and the Caribbean), REF (Eastern Europe and former Soviet Union), and particularly MAF (Middle East and Africa) regions. Projected costs in the indoor sectors had a greater increase in the REF and MAF regions than other regions due to less access to air conditioning, but these figures were surpluses for the OECD90 region (because of overcompensation from increased air conditioning access).

Xia et al. (2018) analyzed both direct and indirect costs. For an industrial sector, direct costs from heatwave-induced productivity loss within that sector, and indirect costs resulted from decreased worktime in other sectors through industrial interdependencies (Orlov et al., 2019; Xia et al., 2018). In Nanjing, they estimated 63.1% of the costs occurred in the manufacturing sector, 14.3% in services, 10.7% in construction, 7.6% in agriculture, 3.3% in energy supply, and 0.9% in mining (Xia et al., 2018). The estimated worktime losses of 4.2–4.5% for outdoor sectors (agriculture, mining and construction) and 0.67–0.7% for indoor sectors alone were not sufficient to explain the costs per sector. Most costs were indirect, resulting from industrial interdependencies with other economic sectors, especially for the manufacturing and energy supply sectors where 88% and 90% of costs, respectively, were indirect. Though the study did not provide the sizes of the sectors' GVP, it did state the manufacturing and service sectors had the largest GVP, which may have partially explained their large cost figures. Agriculture and mining had greater proportions of direct costs; these were sectors with higher work intensities, more exposure to external heat, more occupational health and safety regulations, and relatively fewer industrial interdependencies. Orlov et al. (2019) estimated higher costs from decreased work efficiency in the agricultural sector compared to the construction sector (Orlov et al., 2019). Indirect costs compromised 30–32% of the estimated costs for agriculture. No indirect costs were assumed to occur for construction; the costs for this sector would have increased if this was assumed.

3.5. Worker and workplace characteristics

Four studies investigated the association between costs and different worker and workplace characteristics. These included gender (n = 4), age (n = 4) and business size (n = 2).

3.5.1. Gender

According to a self-administered questionnaire survey in Australia, heat-induced productivity loss was more costly among males than females (Kruskal-Wallis test: 5.45, P-value = 0.0245), despite the two genders having similar numbers (48% of workers were female) and productivity loss levels (30% for both genders) (Zander et al., 2015). The authors stated this could be partially explained by higher median income. However, a similar relative (RR) for injury claims and insurance payouts between males (1.15, 95% CI: 1.1–1.23) and females (1.14, 95% CI: 1.01–1.29) was observed in Guangzhou with a daily WBGT at or above 25 °C (Ma et al., 2019). Despite a similar rate of injury claims within the two genders, females were more influenced by higher heat conditions. Females had a greater increase in insurance payouts when WBGT was 28 °C and 30 °C compared to 24 °C (at 30 °C, RR 1.33, 95% CI: 1.05–1.68); males had smaller, non-statistically significant, increases. However, over three times as many claims and costs from insurance payouts were observed in male workers. Though numbers were not provided, this likely reflects a large male-to-female worker ratio. Xiang et al. (2018) observed a considerably higher number of claims and cost per OHI claim among males compared to females (353 vs 85, and $10,888 vs $3489, respectively), though this was demonstrated using descriptive analysis only (Xiang et al., 2018). A self-reported questionnaire survey in Malaysia estimated a non-statistically significant increase in median cost for females compared to males (median costs of $72.4 and $51.6, respectively, Kruskal-Wallis test: 1.34, P-value = 0.247), with a gender of 1:1 (Zander and Mathew, 2019).

3.5.2. Age

Ma et al. (2019) identified an increased RR for injury claims and insurance payouts in workers aged under 35 years (1.15, 95% CI: 1.04–124), and 35–44 years (1.16, 95% CI: 1.06–1.28), and a non-statistically significant increase in workers above 44 (RR 1.15, 95% CI: 0.99 to 1.32) (Ma et al., 2019). A descriptive analysis by Xiang et al. (2018) showed the number of claims and cost per OHI claim was highest in the 25 to 44 age group relative to other age groups (0–24, 45–64 and 65+), though this was not statistically assessed (Xiang et al., 2018). Zander et al. (2015 and 2019) found no significant correlation between age and associated cost (Zander et al., 2015; Zander and Mathew, 2019).

3.5.3. Business size

Only two studies identified an association between potential costs and business size. Ma et al. (2019) identified increased RRs for injury claims for small- (RR 1.17, 95% CI: 1.08–1.27) and medium-sized businesses (RR 1.16, 95% CI: 1.04–1.29), but not for large businesses (RR 1.06, 95% CI: 0.91–1.28) (Ma et al., 2019). Xiang et al. (2018), on descriptive analysis, identified that although more OHI claims were from employees in larger businesses, employees from medium-sized businesses had greater costs per claim and overall costs (Xiang et al., 2018). Employees from small-sized businesses had lower costs compared to medium- and larger-sized businesses with both fewer claims and lower costs per claim.

4. Discussion

This review summarized estimated costs from occupational heat stress. These costs were large, potentially exceeding $300 billion annually, globally, in previous years (DARA, 2012), with high costs also experienced in individual countries, including nearly $4 billion in Nanjing, China during a heatwave. Considerably greater future costs were projected, with global annual costs increasing by an approximate factor of eight between 2010 and 2030 (DARA, 2012) (Kjellstrom et al., 2019), and costs in Germany increasing by a factor of nearly four from 2004 to 2071–2100 (SRES A1B scenario) (Hübler et al., 2008). Four studies investigated the relationship between temperatures and costs; all observed increasing costs with increasing temperatures, and three observed curvilinear (Costa and Floater, 2020; Takakura et al., 2018; Xiang et al., 2018) instead of linear (Takakura et al., 2017) relationships.

Previous studies have modelled decreased economic output and growth rates as functions of high ambient temperatures, and hypothesized that heat-induced labor output loss is a contributing factor to this function (Dell et al., 2014; Heal and Park, 2016), with one study observing similar decreases in labor output and economic income following high temperatures (Hsiang, 2010). This review identified cost figures to support the function between heat and costs and the similarity between decreased labor productivity and economic burden. However, this review also identified additional expenses following OIs (Ma et al., 2019; Martínez-Solanas et al., 2018; Xiang et al., 2018). Economies incur direct expenses through their healthcare systems and workers' compensation. Employees suffer financially through out-of-pocket payments and lost incomes (Mitra et al., 2017). This can result in reduced consumer spending and hence indirect economic loss. Both heat-related productivity loss and sick leave from OIs decrease labor output; this decreases economic and employer income. Employers may have additional expenses following OIs, such as hiring and training replacement staff (Martínez-Solanas et al., 2018) and potential lawsuits. Minimizing occupational heat stress can reduce financial burden for workers, employers, and the wider economy.

4.1. Projected economic costs that can be avoided

4.1.1. Climate adaptation

Adaptation measures can potentially greatly reduce future economic burden (Costa and Floater, 2020; Morabito et al., 2020; Orlov et al., 2020; Takakura et al., 2018). Costa and Floater (2015) assumed that no air conditioning was available at baseline, likely overestimating the averted cost. This assumption would be more reasonable in low- and middle-instead of high-income countries, where access to air conditioning, and also solar blinds and indoor ventilation, may be limited. However, these measures may be less effective in low- and middle-income countries because financing them is more difficult (Kjellstrom et al., 2016). This may favor measures with less ongoing expenses in these countries such as shifting work hours or working and resting in the shade. Of note, Takakura et al. (2018) observed that a work shift was more effective in low- and middle-than high-income regions (Takakura et al., 2018). Employers globally should adopt adaptation measures to reduce occupational heat stress, both for their workers' safety and to minimize workplace costs. These can include the aforementioned measures and heat management policies, such as training programs, appropriate clothing, adequate water access, and use of mechanical equipment to reduce work intensity (Day et al., 2019; Nunfam et al., 2020). A study in Texas reported that after implementing a heat stress awareness program covering training, improved access to cooling measures and decreased work-rest ratios during high temperatures, the number of OHIs in outdoor workers and associated compensation costs decreased (McCarthy et al., 2019) although total expenses and costs per worker were not reported. Where feasible, companies could substitute labor with capital, such as mechanization, in jobs associated with high levels of heat stress and shift employees into jobs with less heat stress. A gradual shift from agriculture to industrial and service industries has already been observed globally (Pope et al., 2009). Measures affecting workplaces can also be implemented at the government level. These include subsidizing workplace measures such as air conditioning, promoting heat stress awareness, and tax changes such as simultaneously increasing carbon prices and decreasing labor taxes (to decrease associated labor costs from occupational heat stress) (Day et al., 2019; Goulder and Schein, 2013).

4.1.2. Climate mitigation

Projected economic burden was notably more extreme under climate scenarios with higher greenhouse concentrations compared to scenarios with less warming (Hübler et al., 2008; Kovats et al., 2011; Orlov et al., 2020; Takakura et al., 2017, 2018). These results align with previous studies that projected lower labor productivity under projected scenarios with higher greenhouse concentrations (Kjellstrom et al., 2009c, 2016). Climate mitigation is imperative and should minimize most future costs. The IPCC stated that the global mitigation costs of limiting global warming to no more than 2 °C by 2100 is 4.8% of global GDP (Intergovernmental Panel on Climate Change, 2015). Approximately 40% of this cost could be avoided by offsetting the costs from occupational heat stress (Orlov et al., 2020) and more if global warming is limited to less than 1.5 °C (Takakura et al., 2017, 2018). The estimated reductions in costs from climate mitigation were more apparent in later projection time periods, when further global warming is likely to occur (Intergovernmental Panel on Climate Change, 2015). Within the next two decades, similar costs were observed between different climate scenarios (Kjellstrom et al., 2019; Kovats et al., 2011), but over twice the costs were observed by the end of the century under scenarios with higher greenhouse concentrations (Kovats et al., 2011; Orlov et al., 2020; Takakura et al., 2017, 2018). For example, Kovats et al. (2011) projected a potential difference of up to approximately $660 million between scenarios SRES A1B and ENSEMBLES E1 in Europe in 2100 alone. This figure would be greatly increased if the RCP8.5 scenario was used, which assumes no climate mitigation, or if evaluating global costs (DARA, 2012). However, under scenarios with lower greenhouse concentrations, estimated costs in 2070–2100 were similar to those in 2050 (Kovats et al., 2011; Orlov et al., 2020). Costs projected to occur by 2030 are significantly higher than those estimated in 2010 (DARA, 2012; Kjellstrom et al., 2019), indicating that a future increase in costs compared to now likely cannot be avoided, only minimized.

4.2. Costs per industry

Estimated costs were higher in the agriculture (Orlov et al., 2019), construction (Costa and Floater, 2020; Takakura et al., 2017), manufacturing (Costa and Floater, 2020; Xia et al., 2018) and mining sectors (Takakura et al., 2017; Xiang et al., 2018). These industries have been associated with increased morbidity from occupational heat stress due to increased work intensities and higher levels of heat exposure from environmental heat, machinery and/or use of personal protective equipment (Calkins et al., 2019; Kim and Lee, 2019; Moohialdin et al., 2019; Pogačar et al., 2018; Varghese et al., 2018, 2020). The increased cost per claim observed in Xiang et al. (2018) may reflect the greater severity of occupational injuries that occur in the mining sector (Nunfam et al., 2019), which could be exacerbated by heat. This could also hold true for the construction and manufacturing sectors. Workplace guidelines for minimizing occupational heat stress are particularly important for employers in these high-risk industries. This particularly applies for manufacturing businesses, as Xia et al. (2018) observed a large portion of indirect costs occurring in the manufacturing sector (Xia et al., 2018), and indirect costs can be difficult to track. Shifting labor from high-risk sectors to low-risk sectors such as the service sector should reduce future costs from lost worktime and may happen without government intervention (Costa and Floater, 2020; Kovats et al., 2011).

4.3. Regional differences

Based on labor productivity loss, low- and middle-income countries were estimated to have greater GDP percentage losses compared to high-income countries (DARA, 2012; Kjellstrom et al., 2019; Orlov et al., 2020; Roson and Sartori, 2016; Takakura et al., 2017). Low- and middle-income countries are usually more prone to the reduced labor productivity and OIs secondary to heat (Kjellstrom et al., 2009a, 2009b). Dell et al. (2008) observed that in low-income but not high-income countries, a 1 °C increase in monthly mean temperatures was associated with a decrease in economic growth rate by 1.087% (Dell et al., 2008) – this would have at least partially reflected decreased labor productivity. Low- and middle-income countries generally have warmer climates, less protection against occupational heat stress such as air conditioning, and a higher proportion of labor in industrial sectors more prone to industrial heat stress such as outdoor sectors (Kjellstrom et al., 2016, Kjellstrom et al., 2016; Stern, 2006). As observed in Kovats et al. (2014) and Costa and Floater (2015), even in high-income countries, warmer climates, and differences in labor structure can predispose the labor force to greater occupational heat sensitivity (Costa and Floater, 2020; Kovats et al., 2011). Due to decreased wealth, low- and middle-income countries are less likely to adapt to climate change than high-income countries (Intergovernmental Panel on Climate Change, 2015; Kjellstrom et al., 2016; Stern, 2006). This can increase costs from decreased labor productivity and widen the gap in income per capita between low- and high-income countries. High-income countries may also be indirectly affected through global economic effects such as decreased trade.

4.4. Worker and workplace characteristics

4.4.1. Gender

Studies investigating differences in genders' vulnerabilities to temperature increases usually showed small, statistically insignificant differences, and that females were more likely to report heat intolerance than males (Karjalainen, 2012; Pogačar et al., 2017), supporting the increased sensitivity in females observed by Ma et al. (2019). However, this review identified only one study finding a (non-statistically) increase in costs following occupational heat stress among females compared to males (Zander and Mathew, 2019), and three studies observing increased costs among males than females (Ma et al., 2019; Xiang et al., 2018; Zander et al., 2015). This could partially be explained through higher income rates among males (Zander et al., 2015) and male-to-female worker ratios (Ma et al., 2019). Males may be more likely to undertake work with greater physical demand and higher heat stress exposure (Cheung et al., 2016), both increasing their risk of heat-attributable OIs (Adam-Poupart et al., 2015; McInnes et al., 2017) and their severities (leading to large claim payouts). The large gender discrepancy in injury claims observed by Ma et al. (2019) and Xiang et al. (2018) may be partially explained by a higher under-reporting rate among females (Holdcroft, 2007), biasing and exaggerating the increased costs associated with males compared to females. Hence whilst greater costs were observed with males, emphasis should be placed on both genders when considering workplace strategies to minimize heat stress.

4.4.2. Age

Two studies estimated higher relative costs from occupational heat stress in younger workers (aged 25–44 years) due to OIs (Ma et al., 2019; Xiang et al., 2018). This could be because younger workers may be more likely to undertake more physically demanding work associated with a greater risk of OIs (Camino López et al., 2008), including heat-attributable OIs (Bonafede et al., 2016). This could outweigh the increased vulnerability to heat that older adults have compared to younger adults (Basu, 2009; Kenny et al., 2016; Lundgren et al., 2013). Zander et al. (2015 and 2019) observed no difference in costs between age groups due to labor productivity (Zander et al., 2015; Zander and Mathew, 2019). Costs from productivity loss are influenced by income rates. An Australian study identified approximately similar mean income rates across 10-year age groups in workers aged 25 to 64 (Tapper and Fenna, 2019). This could explain the similar costs between different age groups; the respondents in Zander et al. (2015) were centered around 40 years of age and from Australia, and the respondents in Zander and Mathew (2019) had relatively similar ages (most were aged from 20 to 40). Due to the small number of studies investigating age, these findings should only be interpreted as preliminary results.

4.4.3. Business size

Ma et al. (2019) and Xiang et al. (2018) identified greater associations between injury claims from heat-attributable OIs among employees from medium-sized (and also small-sized in Ma et al. (2019)) businesses compared to larger businesses (Ma et al., 2019; Xiang et al., 2018). Large companies have been associated with a lower risk of OIs from all causes (Lundgren et al., 2013; Malchaire, 1999). These companies may have improved facilities and greater enforcement of employee protection measures and education, thus they may be better prepared for managing occupational heat stress.

4.5. Further research

The majority of the literature focused on economic burden from decreased labor productivity based on corresponding recommended work-to-rest ratios or work efficiency. Costs estimated with ISO and NIOSH guidelines were approximately 1.4–2 times larger than those estimated with the Hothaps function (Morabito et al., 2020; Orlov et al., 2019, 2020). The aforementioned guidelines were designed to increase work-rest ratios in order to minimize heat-induced OIs; thus they estimate greater productivity losses than the Hothaps function, which was based on observed productivity without considering work-rest ratios or the minimization of OIs (Bröde et al., 2018; Jacklitsch et al., 2016; Orlov et al., 2020). To compare costs estimated from the two methods and to comprehensively calculate economic expenses, future studies should combine results from estimated decreased work efficiency with those from heat-induced OIs and associated healthcare costs and sick leave. Only a few identified studies investigated costs related to healthcare (Ma et al., 2019; Martínez-Solanas et al., 2018; Xiang et al., 2018) and sick leave (Martínez-Solanas et al., 2018; Zander et al., 2015). Other causes that should be explored further include costs from employees resigning from high heat stress jobs, which to the authors best knowledge has yet to be investigated, and expenses from pain and suffering. Martínez-Solanas et al. (2018) estimated that in Spain, the expenses from pain and suffering exceeded the combined costs from productivity loss and healthcare (Martínez-Solanas et al., 2018). Further research is also warranted in low- and middle-income countries, which were limited to either global studies or two studies investigating retrospective costs in a middle-income country (Das, 2015; Zander and Mathew, 2019).

The costs and benefits of only a few climate adaptation measures were investigated and only in relation to labor productivity (Costa and Floater, 2020; Morabito et al., 2020; Orlov et al., 2019, 2020; Takakura et al., 2018). More measures should be analyzed, including heat management policies and measures at the government level, and should consider other costs such as healthcare costs. Measures can be tailored to specific countries, climate zones and/or industries so that the most effective measures are identified for given work cohorts. Measures were only investigated individually instead of concurrently. Whilst it is easier to determine their impact when investigated separately, implementing and analyzing multiple measures simultaneously may provide more accurate information on the predicted reductions in expenses and identifying which measures are more effective.

Most studies investigated costs in relation to WBGT. WBGT is a useful estimator for the temperature perceived by people and is used by international guidelines to recommend work-rest ratios (International Organizatio, 2017; Jacklitsch et al., 2016; Kjellstrom et al., 2018; Lemke and Kjellstrom, 2012). It considers multiple weather variables to estimate heat stress more comprehensively than air temperature alone (Lemke and Kjellstrom, 2012). The perceived temperature used by Hübler et al. (2008) has similar components to the WBGT (Hübler et al., 2008; Jendritzky et al., 2000; Lemke and Kjellstrom, 2012) and thus should perform similarly. Despite all this, the WBGT is a relatively simple estimator (Budd, 2008; Oliveira et al., 2018) that may not adequately reflect the full range of work situations (D'Ambrosio Alfano et al., 2014). Hence other heat metrics, such as apparent temperature (Steadman, 1984) and the more detailed predicted heat strain (Oliveira et al., 2018), may need to be further explored.

Limited information was identified on the associations of costs with workers' age, gender, business size and associated occupational sectors. These could be explored in future research to obtain more accurate and specific cost estimates. One study from US observed that excluding individual- and workplace-level variables overestimated the decrease in heat-related productivity among fruit pickers (Quiller et al., 2017), though the results were not statistically significant both with and without these variables. Furthermore, these factors may be subject to interaction effects, for example associated costs from different age distributions would vary across different industries. This could provide useful information for developing workplace guidelines and better targeting vulnerable subgroups. Only one study evaluated indirect costs across multiple industrial sectors, observing that they were larger than direct costs (Xia et al., 2018); including and providing estimates from both costs would better illustrate the magnitude of economic expenses.

4.6. Limitations

Whilst multiple databases were searched, the possibility of missing studies cannot be excluded. Studies included in this review were limited to those in English. Countries with high rates of heat stress are often non-English speaking, hence relevant studies may have been missed. This study only considered occupational heat-related costs. Other occupational costs can result from high temperatures without being directly related to workplace heat stress, such as costs from air conditioning and high-temperature employment subsidies (Zhao et al., 2016).

Finally, it should be stressed that all cost figures are estimates and should not to be taken to represent actual figures. Heat stress and its associated costs are influenced by multiple factors at an individual level that would realistically be impossible to calculate precisely (Glass et al., 2015; Stern, 2006). Many costs from labor productivity loss were based on assumed work-to-rest ratios, subjective responses, and/or acclimatization that may not apply to every worker. Healthcare cost estimates exclude costs from unreported OIs; this can potentially exclude many OIs (Missikpode et al., 2019). Projected costs are difficult to predict, because there is notable uncertainty in how climate, labor, and socioeconomic characteristics will change over time (Intergovernmental Panel on Climate Change, 2015; Kjellstrom et al., 2009c).

5. Conclusions

Estimated economic burden from occupational heat stress is substantial. Significant expenses have already occurred which are projected to increase greatly with global warming. Fortunately, most projected costs can be averted with climate change adaptation and mitigation. Further research exploring the relationship between occupational heat stress and costs, in particular expenses from decreased work efficiency and healthcare, and costs stratified by demographics factors is warranted. The development of climate adaptation and mitigation strategies, including workplace heat management policies, are imperative to minimize future heat-attributable economic burden.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2021.110781.

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