

COMMENTARY

Impact of occupational heat stress on worker productivity and economic cost

Margaret C. Morrissey¹  | Gabrielle J. Brewer¹ | Warren Jon Williams² | Tyler Quinn² | Douglas J. Casa¹

¹Department of Kinesiology, Korey Stringer Institute, University of Connecticut, Storrs, Connecticut, USA

²Centers for Disease Control and Prevention (CDC), National Institute for Occupational Safety and Health (NIOSH), National Personal Protective Technology Laboratory (NPPTL), Pittsburgh, Pennsylvania, USA

Correspondence

Margaret C. Morrissey, Department of Kinesiology, Korey Stringer Institute, University of Connecticut, 2095 Hillside Rd U-1110, Storrs, CT 06269, USA.
Email: Margaret.morrissey@uconn.edu

Abstract

Heat stress is a growing concern in the occupational setting as it endangers worker health, safety, and productivity. Heat-related reductions in physical work capacity and missed workdays directly and indirectly cause productivity losses and may substantially affect the economic wellbeing of the organization. This review highlights the physiological, physical, psychological, and financial harms of heat stress on worker productivity and proposes strategies to quantify heat-related productivity losses. Heat stress produces a vicious-cycle feedback loop that result in adverse outcomes on worker health, safety, and productivity. We propose a theoretical model for implementing an occupational heat safety plan that disrupts this loop, preventing heat-related productivity losses while improving worker health and safety.

KEYWORDS

heat stress, occupational, productivity, safety, worker health

1 | INTRODUCTION

There are on average more than 700 heat-related fatalities per year in the United States, which makes environmental heat exposure the leading cause of weather-related deaths.¹ The adverse effects of heat are particularly concerning in vulnerable populations (e.g., elderly, very young, and those with pre-existing medical conditions) as well as workers in occupational settings where there is a significant exposure to heat. According to Gubernot et al.² 359 occupational heat-related deaths were identified between 2000 and 2010, which corresponds to a fatality rate of 0.22 per one million workers. Importantly, fatality estimates may be underestimated due to limitations in occupational surveillance systems and the exclusion of other medical conditions (e.g., sudden cardiac death) which may have been caused by heat stress. A large-scale epidemiological investigation (Washington, USA) examining the influence of environmental heat on traumatic injuries derived from workers compensation claims reported that heat-exposed agricultural workers were 14% more likely to experience a traumatic injury compared to nonheat exposed agricultural workers.³

This is problematic as approximately 13.3 million workers are exposed to extreme heat every day in the United States.⁴ These numbers are projected to increase as environmental temperatures continue to rise as a result of our changing climate.

Further, a potential threat to the health and safety of workers exposed to heat is its burden on the economy.^{5–7} Predicted global costs from lost worktime due to occupational heat stress is 2.4–2.5 trillion dollars in 2030 and up to 4.0% of GDP by 2100.⁶ The financial burden of occupational heat stress is likely the result of heat-related occupational injuries and illnesses (e.g., healthcare costs, sick leave, injury compensation claims) and decreased labor output or *productivity* (e.g., lower economic production, maintenance cost for lower production).^{7–10} Current research suggests that productivity losses directly contribute to decreased economic output as a function of high ambient temperature.^{11,12} A meta-analysis found that 30% of workers reported work productivity losses with a 2.6% productivity decline for each degree above 24°C wet bulb globe temperature (WBGT).¹³ The following sections will briefly outline mechanisms that cause heat-related productivity losses (i.e., presenteeism and

absenteeism), quantifying productivity and economic losses associated with heat stress, and strategies to mitigate the adverse effects of heat, thereby alleviating the economic burden. The objective of this document is to present the negative consequences of occupational heat stress (physiologically, physically, psychologically, financially) to encourage occupational heat safety plan implementation.

2 | HEAT-RELATED PRESENTEEISM

Work capacity in the heat is dependent on three key factors: the intensity of physical work (i.e., metabolic heat production), the clothing or personal protective equipment worn, and workplace or environmental conditions.^{14,15} The combined effects of metabolic rate, clothing, and workplace conditions have been shown to induce hyperthermia (i.e., increased core temperature),¹³ accelerate dehydration,^{16–19} and alter perceptual and subjective responses to heat.^{17,20–23} Together, these factors transform physical working conditions^{3,6} and introduce potential hazards to the work setting (e.g., grip problems from sweat, sweat in eyes, distraction, and time-off-task) (Figure 1). All factors presented in Figure 1 describe heat-related presenteeism, which can be defined as losses in productivity when workers are not fully functioning in the workplace (i.e., reductions in physical capacity) due to heat stress.²²

Zander et al.²⁴ reported that approximately 1214 workers surveyed were 35% less productive on days they indicated experiencing heat stress. Research has suggested that 40%–70% of workers arrive at work dehydrated, which consequentially results in losses in productivity on a hot and/or humid workday. Prework dehydration can result from factors such as low water intake, consumption of caffeine beverages in lieu of water intake, and after-shift alcohol consumption.^{17,25,26} Dehydration and hyperthermia can further exacerbate physical work capacity.¹⁷ Dehydration and hyperthermia compromise cardiovascular function by increasing heart rate and reducing heart rate variability, cardiac output, and cerebral blood flow.^{27–30} Nybo et al.³⁰ reported an 18% reduction in cerebral blood flow when

esophageal temperatures were 39.5°C compared to 37.5°C following exercise in the heat. Dehydration and/or hyperthermia-induced alterations in cerebral blood flow,^{30,31} as well as, greater heat production in the brain can impair cognitive function,³¹ motor-cognitive function, complex motor tasks, and promote psychological strain (e.g., increase thermal sensation, decrease thermal comfort).^{17,32–34} Research has suggested that brain activity under hyperthermia is altered through increases in brain catecholamines and an increase in the ratio between alpha and beta wave frequency.³¹ These changes are linked to decrements in cognition, arousal, and perception of physical exertion, all of which can increase fatigue and result in reductions in working capacity.³¹ Tasks that are considered complex cognitive tasks, are more frequently impaired during hyperthermia and dehydration.¹⁷ This is particularly concerning as many workers are required to perform skillful and dangerous work in hot conditions.

Cognitive decrements not only impair worker production output (i.e., physical work capacity) but can increase risk of injury at the worksite.⁶ For example, a case-crossover study in outdoor construction workers reported a 0.5% increase in the odds of traumatic injuries per 1°C increase in maximum daily humidex (odds ratio 1.005 [95% CI 1.003–1.007]).³⁵ Changes in the work environment induced by heat exposure can also influence the occurrence of workplace injuries. For example, safety goggles can fog, sweat can get in workers' eyes, and sweaty hands can reduce grip on tools. Productivity losses also can result from costs associated with sick leave (i.e., paying other employees to work overtime or replacing staff), healthcare costs, and injury compensation claims.⁶

3 | HEAT-RELATED ABSENTEEISM

Heat-related productivity losses can also come in the form of absenteeism, which is characterized as employee absence from work due to adverse effects.²⁴ Occupational heat exposure has been shown to increase risk of heat-related illness/injury, occupational injuries, cardiac events, and renal injury.^{3,18,35–40} When these injuries and illnesses

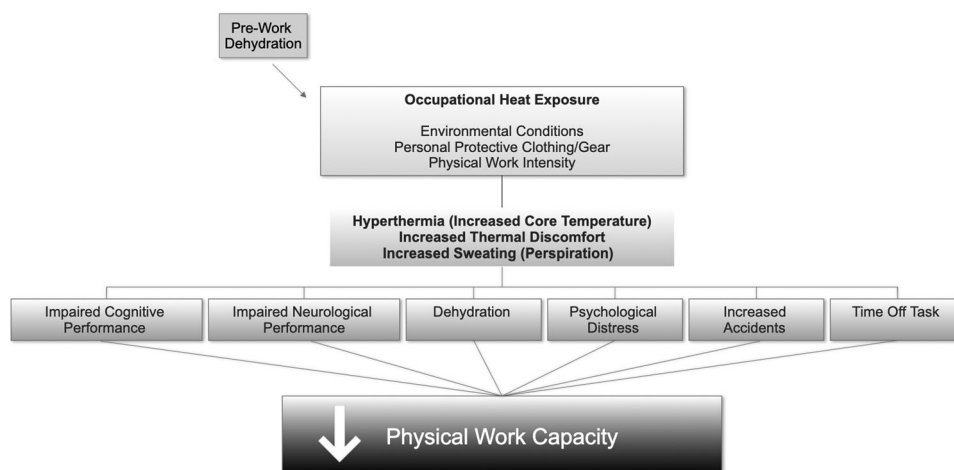


FIGURE 1 Etiology of reduced physical work capacity due to occupational heat stress [Color figure can be viewed at wileyonlinelibrary.com]

occur, employers are subject to worker compensation claims insurance pay outs, medical fees, subsidies, and additional expenses to hire and train new replacement staff.^{6,41} Lawsuits associated with heat-related fatalities and injuries also contribute to the heavy economic burden of heat.⁴¹ Employers can also suffer indirect costs from out-of-pocket payments and lost incomes, resulting in reduced consumer spending.⁴²

Several investigations have estimated the economic burden of heat stress.^{6,8,41,43} Martínez-Solanas et al.⁴¹ reported that one-half million occupational injuries could be attributable to nonoptimal temperatures, which corresponds to an estimated 13 million person-days of work lost in Spain due to temperature, or an annual average of 42 days per 1000 workers. The estimated annual economic burden for Spain is 370 million US dollars (USD). ClimateCost⁴⁴ reported that total productivity losses due to climate change could cost Europe between 300 and 700 million USD by 2080. The global costs associated with lost worktime due to heat were 280 billion USD in 1995 and 311 billion USD in 2010 ($\approx 0.5\%$ of GDP) and continue to rise.⁶ As hot workdays are projected to increase due to climate change, employers must implement strategies to reduce the multitude of risks associated with heat exposure.

4 | MONETIZATION OF HEAT-RELATED PRODUCTIVITY LOSSES

Assessing the economic burden of health-related losses in productivity is not new as many instruments and surveys have been developed to assess time lost to health-related conditions (i.e., absenteeism) and reductions in physical capacity during work (presenteeism).^{45,46} Employers are particularly focused on time lost as it is easier to quantify missed workdays and absent hours per week.⁴⁵ However, employers must recognize that recent literature suggests that health-related presenteeism may account for a larger proportion of losses than absenteeism, accounting for up to three-fifths of the total USD lost.⁴⁵ Although there are no current studies that assess the contribution of presenteeism and absenteeism associated heat-

related productivity losses, it is difficult to ignore this statistic calculated from various health-related and medical conditions.

As the evidence linking occupational heat stress and economic costs continues to grow, methods to estimate productivity losses associated with presenteeism have been examined and developed.^{8,9,13,45,47} Survey-based methods require workers to recall information related to their perception of physical impairment or estimate unproductive time while at work.⁴⁵ This becomes challenging as it is self-reported data that must assume that workers' perceptions are accurate. To address these challenges, many studies have modeled labor output as a function of occupational heat stress to quantify the economic burden associated with presenteeism.^{43,47} Within these models, occupational heat stress is typically quantified as Wet Bulb Globe Temperature (WBGT), which allows employers to measure the environmental conditions of their worksite and then input this data into the corresponding model.^{10,43,48} To estimate productivity losses that drive increased economic losses, various models^{10,43,48} utilize a risk function equation to convert WBGT into percent productivity loss (PL %). Figure 2 presents different risk function models that can be used to estimate productivity losses.⁴³

Although risk functions may provide valuable information on productivity losses associated with certain WBGT, the models require several assumptions that must be recognized.

First, it assumes that workers have the ability to reduce their work intensity to avoid clinical health problems.³⁹ Vulnerable workers and workers that are paid on a piece-pay system may not adjust their pace based on their body's feedback to heat.⁴³ Additionally, workers may choose to continue to work at unsafe work intensities if they have received little education on the signs and symptoms of impending heat illness and may succumb to heat illness when it could have been avoided.^{49,50} Second, data used to create these models were based on work to rest ratios and epidemiological data that are specific to only a few occupations and based on well-conditioned, male workers. This may lead to underestimated productivity loss estimates for those who are unfit⁴⁷ and inaccurate productivity estimates for women. Moreover, the models are created from

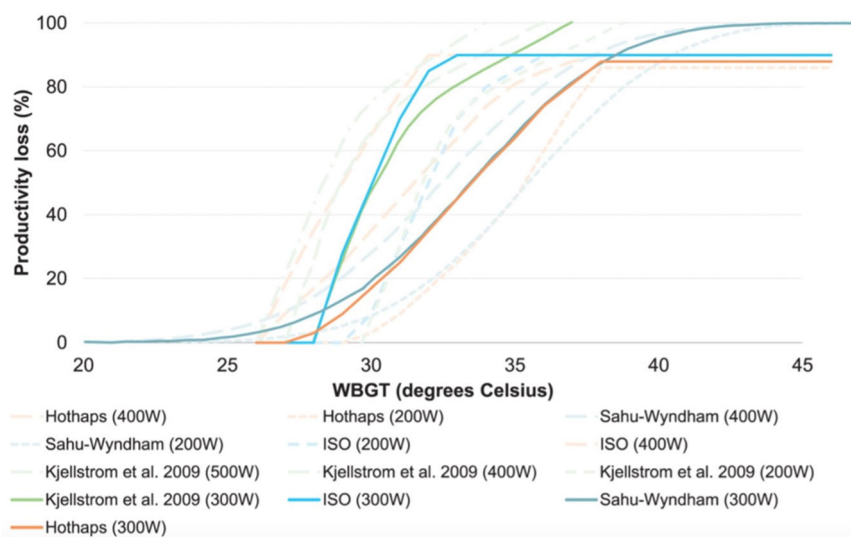


FIGURE 2 Risk function models for occupational heat stress and productivity losses. Figure from Day et al. (2019) [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

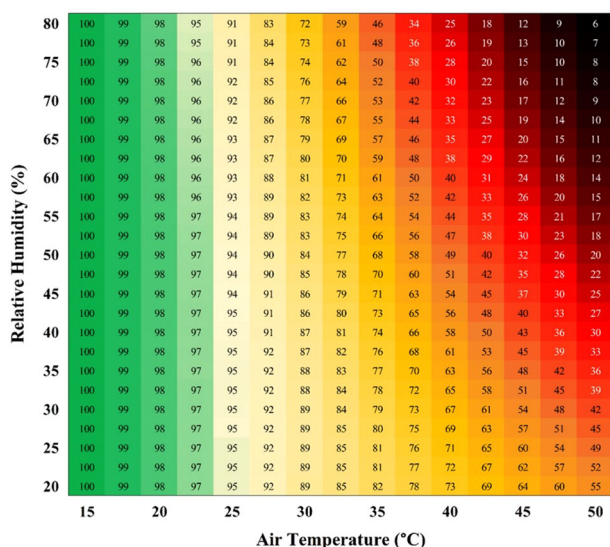


FIGURE 3 Graphical formula for worker physical work capacity as percentage of full working capacity based on air temperature and relative humidity. Figure is from Foster et al. (2021)⁴⁷ [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

laboratory studies and a model based on real-life observations has yet to be developed. Lastly, as the models are currently presented, it is difficult for employers and safety managers to utilize the data to protect their workers. To address the adaptability of these models into the work setting, Foster et al.⁴⁷ has proposed an advanced empirical model that quantifies the impact of heat on physical work capacity and translates it to productivity losses. The model uses air temperature and relative humidity to estimate heat stress. The model is also presented as a graphical formula (Figure 3) to estimate workers' physical work capacity based on these environmental factors. This tool can be utilized to quantify reductions in physical work capacity to determine what heat mitigation strategies are required. For example, if the air temperature is 35°C and relative humidity is 40%, employers should expect a 26% reduction in physical work capacity (working at 74% of full 100% capacity).

To monetize reductions in physical work capacity in the heat, Morabito et al.¹⁰ also present a daily economic cost estimator that can be used to determine how much economic cost will be lost on days where workers experience heat stress (Equation 1). The daily economic cost calculator requires productivity lost or reduction in physical

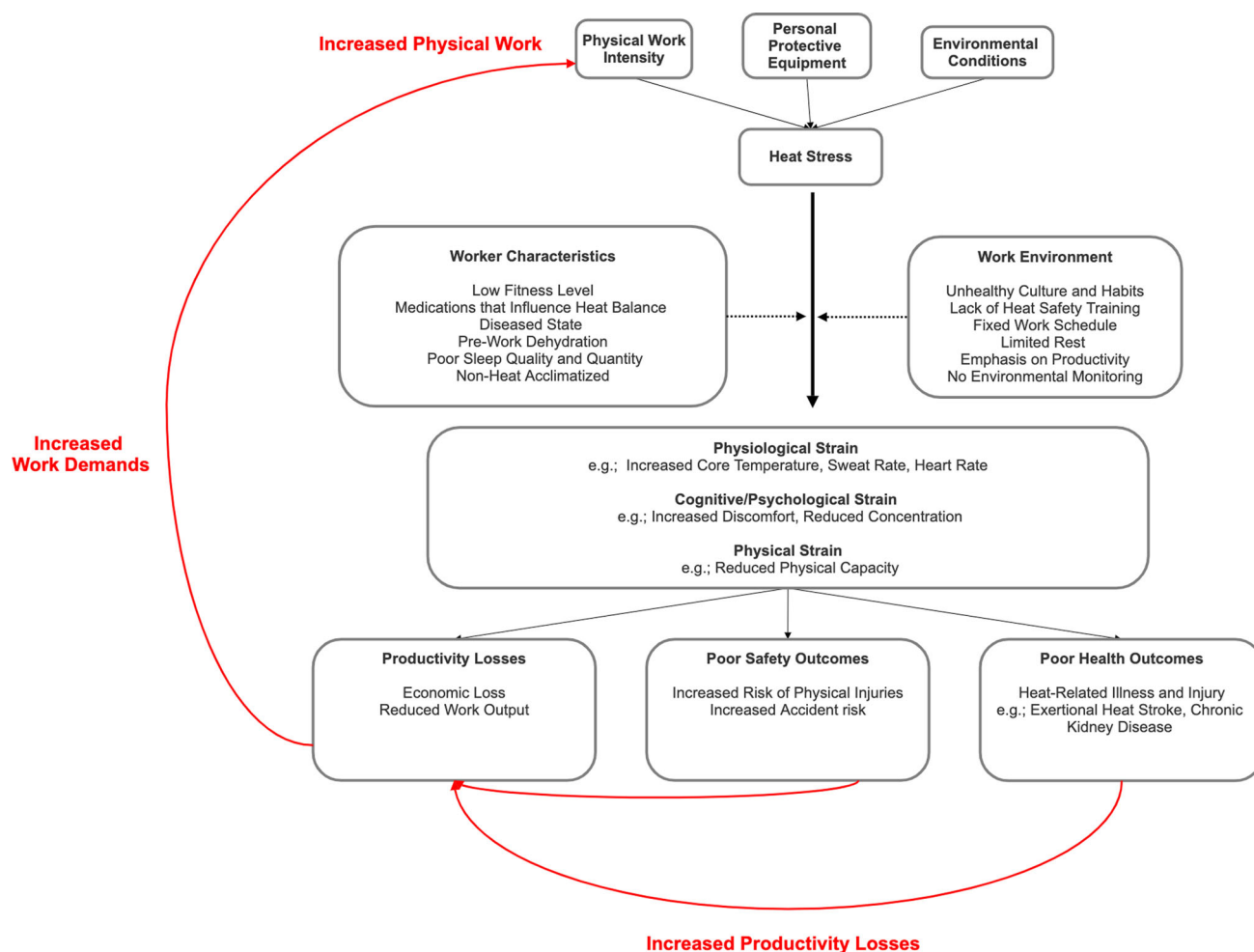


FIGURE 4 Heat-induced productivity loss positive feedback resulting in negative consequences of occupational heat stress that result in productivity [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

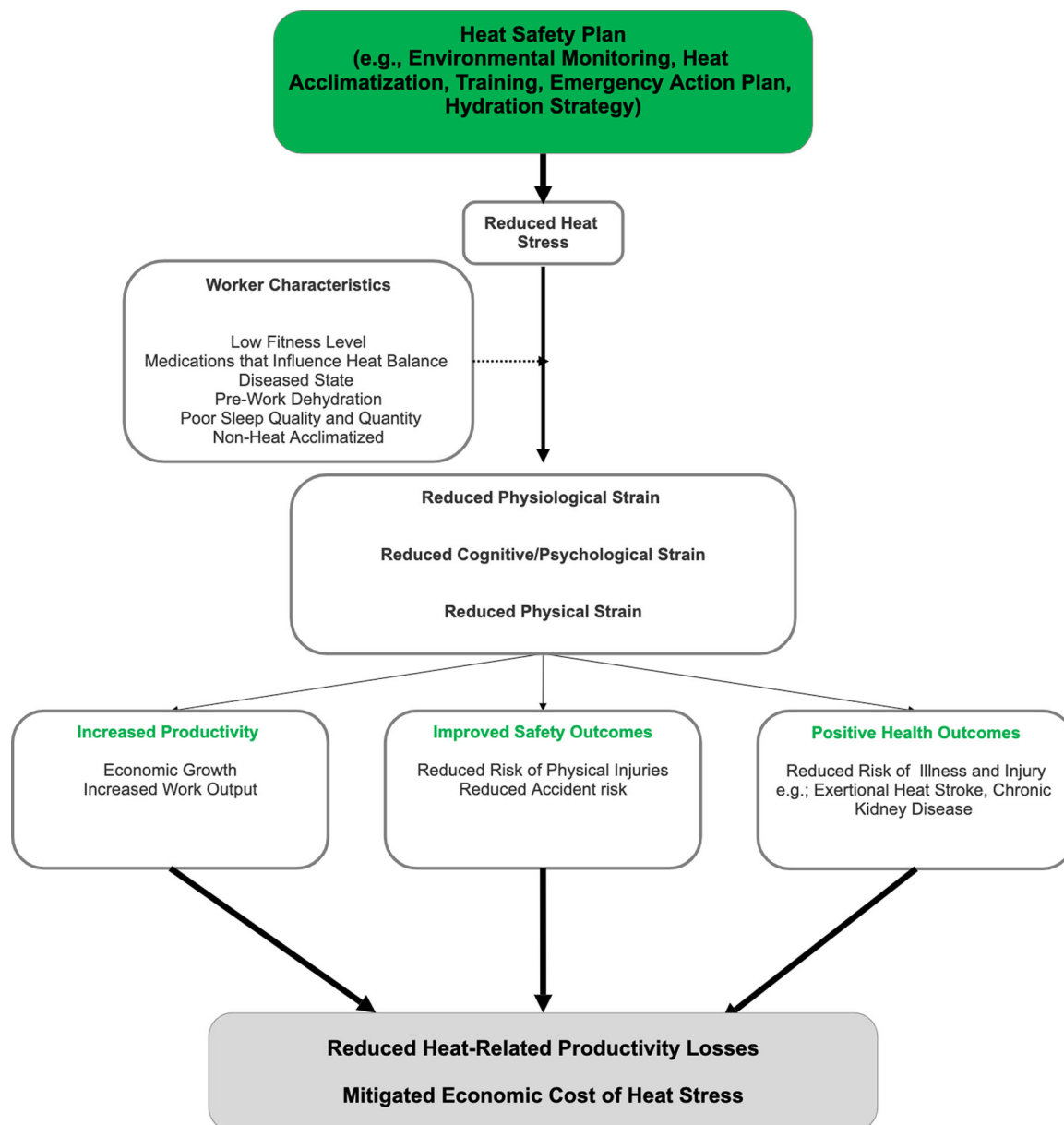


FIGURE 5 The benefits of implementing a heat safety plan on productivity and economic cost [Color figure can be viewed at wileyonlinelibrary.com]

work capacity to calculate. This equation is particularly informative as it presents monetization of heat-related presenteeism.

$$\text{Economic cost} = \text{Worker's daily salary} \times \text{Productivity Losses}(\%) \quad (1)$$

Other methods focus on absenteeism and calculate days or hours "lost" to heat at various environmental conditions.⁴⁵ These methods are difficult as many workers will be replaced if absent from work. These factors also do not consider work to rest ratios that are required in dangerous environmental heat for safety and quality of work considerations.

Overall, these methods that allow for estimation of costs associated with the dangers of heat will further entice employers to

consider life-saving heat safety program that not only reduce productivity losses but enhance health and safety.

5 | HEAT SAFETY PLANS MAINTAIN PRODUCTIVITY, SAFETY AND HEALTH OF WORKERS

Although in many cases, employers are invested in both the health of their workers and the wealth of the organization, some employers may discourage heat safety interventions if they perceive it as barrier to economic growth.⁵¹ It is important for employers to recognize that health/safety and productivity do not oppose one another, rather, health and safety initiatives have been shown to dramatically improve

productivity.^{7,10} Morabito et al. and Orlov et al. examined the influence of a heat stress mitigation strategy, specifically working in the shade, on costs associated with productivity alterations. Both studies estimated that when workers were performing work under the shade, there were 6- and 10-fold (respectively) increases in productivity.^{7,10} Moreover, Morabito et al. (2020) reported that moving a working shift 2 h earlier to avoid heat stress reduced costs by 33%. By contrast, Figure 4 proposes a theoretical model expressing the negative consequences of occupational heat stress. Physical work, personal protective equipment, and the environment can produce heat stress, which is exacerbated with various workplace and worker characteristics. The interplay between these characteristics and heat stress produces negative physiological, cognitive, psychological, and physical outcomes. When poor health, safety, and productivity outcomes are incurred as a result of occupational heat stress (and corresponding physiological strain) it is likely to produce a “positive” feedback loop that continues to subject workers to greater levels of heat strain by increasing work demands. This would result in a positive feedback loop with negative consequences. The positive feedback loop occurs through working overtime or increasing physical work capacity to eliminate the financial burden caused by heat. Figure 5 presents how an effective heat safety plan will mitigate the detrimental effects of heat while preserving productivity. Implementing heat safety mitigation strategies such as body cooling, heat acclimatization, and hydration has been shown to significantly reduce the physiological, cognitive, psychological, and physical strain induced by heat stress and therefore, can disrupt the positive feedback loop that produces increased productivity losses from poor safety and health outcomes.^{52–56} Limiting losses of productivity through heat safety initiatives also supports the organization's financial wellbeing. For example, implementing a heat safety plan can limit re-hiring of staff, paying for overtime hours, and reduce costs associated with worker compensation claims after a worker experiences a heat-related illness. McCarthy et al. reported that after implementing a heat safety plan, median cost incurred per heat-related illness reduced to \$208 compared to \$416 in the prior 2 years. Moreover, there can be legal ramifications for the employer should the worker suffer a heat-related injury or illness on the job. There may be worker's compensation and potential negligence issues that may play into an injury that might be deemed preventable had the employer implemented a heat safety plan. Therefore, employers and safety managers must consider the multitude of benefits of heat safety programs for not only the employee, but for the employer as well.^{57,58} To determine appropriate heat mitigation strategies for the workplace, Morrissey et al. present evidence-based, feasible recommendations regarding occupational heat safety practices and procedures to implement.⁵⁸

6 | CONCLUSION

Occupational heat stress causes several physical, physiological, and psychological responses that negatively impact worker productivity. Heat-related productivity losses also have a substantial effect on the economic wellbeing of the organization and economy. Quantifying productivity losses or physical work capacity associated with heat

and the forming a heat safety plan will reduce economic costs while promoting the health and safety of workers. Moreover, employers may avoid legal exposure from job-related heat injuries as many may be preventable through a heat safety program. These injuries can be perceived as organizational negligence rather than an unfortunate accident that could not have been prevented. Therefore, employers and safety managers should implement a heat safety plan to benefit their organization and keep workers safe.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

DISCLOSURE BY AJIM EDITOR OF RECORD

John Meyer declares that he has no conflict of interest in the review and publication decision regarding this article.

AUTHOR CONTRIBUTIONS

Margaret C. Morrissey conceptualized the idea for this commentary; Margaret C. Morrissey and Gabrielle J. Brewer contributed to the acquisition and summary of key content for the manuscript; all authors contributed to the drafting and review of the manuscript; Douglas J. Casa, Tyler Quinn, and W. Jon Williams revised manuscript critically for important intellectual content; and all authors participated in the final approval of the version to be published and agree to be accountable for all aspects of the work.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Center for Disease Control and Prevention. Mention of a product or use of a photo does not constitute NIOSH endorsement.

ORCID

Margaret C. Morrissey  <http://orcid.org/0000-0002-4488-3648>

REFERENCES

1. Vaidyanathan A. Heat-related deaths—United States, 2004–2018. *MMWR Morb Mortal Wkly Rep.* 2020;69:729–734. <https://doi.org/10.15585/mmwr.mm6924a1>
2. Gubernot DM, Anderson GB, Hunting KL. Characterizing occupational heat-related mortality in the United States, 2000–2010: an analysis using the census of fatal occupational injuries database. *Am J Ind Med.* 2015;58:203–211. <https://doi.org/10.1002/ajim.22381>
3. Spector JT, Bonauto DK, Sheppard L, et al. A case-crossover study of heat exposure and injury risk in outdoor agricultural workers. *PLOS One.* 2016;11:e0164498. <https://doi.org/10.1371/journal.pone.0164498>
4. Tanglis M. It is time to protect Millions of Workers From Extreme Heat. *CitizenVox*; 2018. Accessed April 6, 2021. <https://citizenvox.org/2018/07/17/workers-in-extreme-heat/>

5. Ma R, Zhong S, Morabito M, et al. Estimation of work-related injury and economic burden attributable to heat stress in Guangzhou, China. *Sci Total Environ*. 2019;666:147-154. <https://doi.org/10.1016/j.scitotenv.2019.02.201>
6. Borg MA, Xiang J, Anikeeva O, et al. Occupational heat stress and economic burden: a review of global evidence. *Environ Res*. 2021; 195:110781. <https://doi.org/10.1016/j.envres.2021.110781>
7. Orlov A, Sillmann J, Aaheim A, Aunan K, de Bruin K. Economic losses of heat-induced reductions in outdoor worker productivity: a case study of Europe. *Econ Disasters Clim Change*. 2019;3:191-211. <https://doi.org/10.1007/s41885-019-00044-0>
8. Kjellstrom T, Holmer I, Lemke B. Workplace heat stress, health and productivity—an increasing challenge for low and middle-income countries during climate change. *Glob Health Action*. 2009;2:2047. <https://doi.org/10.3402/gha.v2i0.2047>
9. Lundgren K, Kuklane K, Venugopal V. Occupational heat stress and associated productivity loss estimation using the PHS model (ISO 7933): a case study from workplaces in Chennai, India. *Glob Health Action*. 2014;7:25283. <https://doi.org/10.3402/gha.v7.25283>
10. Morabito M, Messeri A, Crisci A, et al. Heat-related productivity loss: benefits derived by working in the shade or work-time shifting. *Int J Product Perform Manag*. 2020;70:507-525. <https://doi.org/10.1108/IJPPM-10-2019-0500>
11. Heal G, Park J. Reflections—temperature stress and the direct impact of climate change: a review of an emerging literature. *Rev Environ Econ Policy*. 2016;10:347-362. <https://doi.org/10.1093/reep/rew007>
12. Dell M, Jones BF, Olken BA. What do we learn from the weather? The new climate-economy literature. *J Econ Lit*. 2014;52:740-798. <https://doi.org/10.1257/jel.52.3.740>
13. Flouris AD, Dinas PC, Ioannou LG, et al. Workers' health and productivity under occupational heat strain: a systematic review and meta-analysis. *Lancet Planet Health*. 2018;2:e521-e531. [https://doi.org/10.1016/S2542-5196\(18\)30237-7](https://doi.org/10.1016/S2542-5196(18)30237-7)
14. Gao C, Kuklane K, Östergren P-O, Kjellstrom T. Occupational heat stress assessment and protective strategies in the context of climate change. *Int J Biometeorol*. 2018;62:359-371. <https://doi.org/10.1007/s00484-017-1352-y>
15. Bernard TE, Ashley CD. Short-term heat stress exposure limits based on wet bulb globe temperature adjusted for clothing and metabolic rate. *J Occup Environ Hyg*. 2009;6:632-638. <https://doi.org/10.1080/15459620903133642>
16. Chapman CL, Johnson BD, Vargas NT, Hostler D, Parker MD, Schlader ZJ. Both hyperthermia and dehydration during physical work in the heat contribute to the risk of acute kidney injury. *J Appl Physiol*. 2020;128:715-728. <https://doi.org/10.1152/jappphysiol.00787.2019>
17. Piil JF, Lundbye-Jensen J, Christiansen L, et al. High prevalence of hypohydration in occupations with heat stress—perspectives for performance in combined cognitive and motor tasks. *PLOS One*. 2018;13:e0205321. <https://doi.org/10.1371/journal.pone.0205321>
18. Butler-Dawson J, Krisher L, Yoder H, et al. Evaluation of heat stress and cumulative incidence of acute kidney injury in sugarcane workers in Guatemala. *Int Arch Occup Environ Health*. 2019;92: 977-990. <https://doi.org/10.1007/s00420-019-01426-3>
19. Mix J, Elon L, Vi Thien Mac V, et al. Hydration status, kidney function, and kidney injury in Florida agricultural workers. *J Occup Environ Med*. 2018;60:e253-e260. <https://doi.org/10.1097/JOM.0000000000001261>
20. Gun RT, Budd GM. Effects of thermal, personal and behavioural factors on the physiological strain, thermal comfort and productivity of Australian shearers in hot weather. *Ergonomics*. 1995;38: 1368-1384. <https://doi.org/10.1080/00140139508925195>
21. Ioannou LG, Tsoutsoubi L, Mantzios K, et al. The impacts of sun exposure on worker physiology and cognition: multi-country evidence and interventions. *Int J Environ Res Public Health*. 2021;18: 7698. <https://doi.org/10.3390/ijerph18147698>
22. Piil JF, Christiansen L, Morris NB, et al. Direct exposure of the head to solar heat radiation impairs motor-cognitive performance. *Sci Rep*. 2020;10:7812. <https://doi.org/10.1038/s41598-020-64768-w>
23. Carter S, Field E, Oppermann E, Brearley M. The impact of perceived heat stress symptoms on work-related tasks and social factors: a cross-sectional survey of Australia's Monsoonal North. *Appl Ergon*. 2020;82:102918. <https://doi.org/10.1016/j.apergo.2019.102918>
24. Zander KK, Botzen WJW, Oppermann E, Kjellstrom T, Garnett ST. Heat stress causes substantial labour productivity loss in Australia. *Nat Clim Change*. 2015;5:647-651. <https://doi.org/10.1038/ndclimate2623>
25. Zhang Y, Balilionis G, Casaru C, et al. Effects of caffeine and menthol on cognition and mood during simulated firefighting in the heat. *Appl Ergon*. 2014;45:510-514. <https://doi.org/10.1016/j.apergo.2013.07.005>
26. Shirreffs SM, Maughan RJ. Restoration of fluid balance after exercise-induced dehydration: effects of alcohol consumption. *J Appl Physiol*. 1997;83:1152-1158. <https://doi.org/10.1152/jappl.1997.83.4.1152>
27. González-Alonso J, Crandall CG, Johnson JM. The cardiovascular challenge of exercising in the heat. *J Physiol*. 2008;586:45-53. <https://doi.org/10.1113/jphysiol.2007.142158>
28. González-Alonso J, Mora-Rodríguez R, Below PR, Coyle EF. Dehydration markedly impairs cardiovascular function in hyperthermic endurance athletes during exercise. *J Appl Physiol Bethesda Md* 1985. 1997;82: 1229-1236. <https://doi.org/10.1152/jappl.1997.82.4.1229>
29. Trites DG, Robinson DG, Banister EW. Cardiovascular and muscular strain during a tree planting season among British Columbia silviculture workers. *Ergonomics*. 1993;36:935-949. <https://doi.org/10.1080/00140139308967958>
30. Nybo L, Møller K, Volianitis S, Nielsen B, Secher NH. Effects of hyperthermia on cerebral blood flow and metabolism during prolonged exercise in humans. *J Appl Physiol Bethesda Md* 1985. 2002; 93:58-64. <https://doi.org/10.1152/jappphysiol.00049.2002>
31. Hasegawa H, Cheung SS. Hyperthermia effects on brain function and exercise capacity. *J Phys Fit Sports Med*. 2013;2:429-438. <https://doi.org/10.7600/jpfs.2.429>
32. Adan A. Cognitive performance and dehydration. *J Am Coll Nutr*. 2012; 31:71-78. <https://doi.org/10.1080/07315724.2012.10720011>
33. Cian C, Barraud PA, Melin B, Raphael C. Effects of fluid ingestion on cognitive function after heat stress or exercise-induced dehydration. *Int J Psychophysiol Off J Int Organ Psychophysiol*. 2001;42: 243-251.
34. Gaoua N, Herrera CP, Périard JD, El Massioui F, Racinais S. Effect of passive hyperthermia on working memory resources during simple and complex cognitive tasks. *Front Psychol*. 2018;8:2290. <https://doi.org/10.3389/fpsyg.2017.02290>
35. Calkins MM, Bonauto D, Hajat A, et al. A case-crossover study of heat exposure and injury risk among outdoor construction workers in Washington State. *Scand J Work Environ Health*. 2019;45: 588-599. <https://doi.org/10.5271/sjweh.3814>
36. Tustin AW, Lamson GE, Jacklitsch BL, et al. Evaluation of occupational exposure limits for heat stress in outdoor workers—United States, 2011-2016. *MMWR Morb Mortal Wkly Rep*. 2018;67: 733-737. <https://doi.org/10.15585/mmwr.mm6726a1>
37. Pradhan B, Kjellstrom T, Atar D, et al. Heat stress impacts on cardiac mortality in nepali migrant workers in Qatar. *Cardiology*. 2019;143: 37-48. <https://doi.org/10.1159/000500853>
38. Dehghan H, Mortazavi SB, Jafari MJ, Maracy MR. Cardiac strain between normal weight and overweight workers in hot/humid weather in the Persian Gulf. *Int J Prev Med*. 2013;4:1147-1153.
39. Hansson E, Glaser J, Jakobsson K, et al. Pathophysiological mechanisms by which heat stress potentially induces kidney inflammation and chronic kidney disease in sugarcane workers. *Nutrients*. 2020;12:1639. <https://doi.org/10.3390/nu12061639>

40. Johnson RJ, Wesseling C, Newman LS. Chronic kidney disease of unknown cause in agricultural communities. *N Engl J Med*. 2019;380:1843-1852. <https://doi.org/10.1056/NEJMr1813869>
41. Martínez-Solanas È, López-Ruiz M, Wellenius GA, et al. Evaluation of the impact of ambient temperatures on occupational injuries in Spain. *Environ Health Perspect*. 2018;126:067002. <https://doi.org/10.1289/EHP2590>
42. Mitra S, Palmer M, Kim H, Mont D, Groce N. Extra costs of living with a disability: a review and agenda for research. *Disabil Health J*. 2017;10:475-484. <https://doi.org/10.1016/j.dhjo.2017.04.007>
43. Day E, Fankhauser S, Kingsmill N, Costa H, Mavrogianni A. Upholding labour productivity under climate change: an assessment of adaptation options. *Clim Policy*. 2019;19:367-385. <https://doi.org/10.1080/14693062.2018.1517640>
44. ClimateCost. Economics of climate change. ClimateCost Home. Accessed April 17, 2021. <http://www.climatecost.cc/>
45. Mattke S, Balakrishnan A, Bergamo G, Newberry SJ. A review of methods to measure health-related productivity loss. *Am J Manag Care*. 2007;13:211-217.
46. Mitchell RJ, Bates P. Measuring health-related productivity loss. *Popul Health Manag*. 2011;14:93-98. <https://doi.org/10.1089/pop.2010.0014>
47. Foster J, Smallcombe JW, Hodder S, et al. An advanced empirical model for quantifying the impact of heat and climate change on human physical work capacity. *Int J Biometeorol*. 2021;65:1-15. <https://doi.org/10.1007/s00484-021-02105-0>
48. Kjellstrom T, Freyberg C, Lemke B, Otto M, Briggs D. Estimating population heat exposure and impacts on working people in conjunction with climate change. *Int J Biometeorol*. 2018;62:291-306. <https://doi.org/10.1007/s00484-017-1407-0>
49. Luque JS, Becker A, Bossak BH, Grzywacz JG, Tovar-Aguilar JA, Guo Y. Knowledge and practices to avoid heat-related illness among hispanic farmworkers along the Florida-Georgia line. *J Agromedicine*. 2020;25:190-200. <https://doi.org/10.1080/1059924X.2019.1670312>
50. El-Shafei DA, Bolbol SA, Awad Allah MB, Abdelsalam AE. Exertional heat illness: knowledge and behavior among construction workers. *Environ Sci Pollut Res*. 2018;25:32269-32276. <https://doi.org/10.1007/s11356-018-3211-8>
51. Morris NB, Levi M, Morabito M, et al. Health vs. wealth: employer, employee and policy-maker perspectives on occupational heat stress across multiple European industries. *Temperature*. 2020;0:1-18. <https://doi.org/10.1080/23328940.2020.1852049>
52. Biggs C, Paterson M, Maunder E. Hydration status of South African forestry workers harvesting trees in autumn and winter. *Ann Occup Hyg*. 2011;55:6-15. <https://doi.org/10.1093/annhyg/meq.068>
53. Brake DJ, Bates GP. Fluid losses and hydration status of industrial workers under thermal stress working extended shifts. *Occup Environ Med*. 2003;60:90-96. <https://doi.org/10.1136/oem.60.2.90>
54. Brearley MB, Norton IN, Trewin AS. The case for heat acclimatization of disaster responders—an Australian perspective. *Front Public Health*. 2017;5:98. <https://doi.org/10.3389/fpubh.2017.00098>
55. Chicas R, Xiuhtecutli N, Dickman NE, et al. Cooling intervention studies among outdoor occupational groups: a review of the literature. *Am J Ind Med*. 2020;63:988-1007. <https://doi.org/10.1002/ajim.23175>
56. Morris NB, Jay O, Flouris AD, et al. Sustainable solutions to mitigate occupational heat strain—an umbrella review of physiological effects and global health perspectives. *Environ Health*. 2020;19:95. <https://doi.org/10.1186/s12940-020-00641-7>
57. McCarthy RB, Shofer FS, Green-McKenzie J. Outcomes of a heat stress awareness program on heat-related illness in municipal outdoor workers. *J Occup Environ Med*. 2019;61:724-728. <https://doi.org/10.1097/JOM.0000000000001639>
58. Morrissey MC, Casa DJ, Brewer GJ, et al. Heat safety in the workplace: modified Delphi consensus to establish strategies and resources to protect U.S workers. *GeoHealth*. 2021;5:2021.

How to cite this article: Morrissey MC, Brewer GJ, Williams WJ, Quinn T, Casa DJ. Impact of occupational heat stress on worker productivity and economic cost. *Am J Ind Med*. 2021;1-8. <https://doi.org/10.1002/ajim.23297>