

# Impact of climate change on occupational health and productivity: a systematic literature review focusing on workplace heat

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**KEY WORDS:** Climate change; heat-related illness; occupational diseases; occupational injury; productivity; vector-borne infectious diseases

**PAROLE CHIAVE:** Cambiamenti climatici; infortuni sul lavoro; malattie da calore; malattie professionali; malattie trasmesse da vettori; produttività

## SUMMARY

**Background:** *With climate change, mean annual air temperatures are getting hotter and extreme weather events will become more and more common in most parts of the world.* **Objectives:** *As part of the EU funded project HEAT-SHIELD we conducted a systematic review to summarize the epidemiological evidence of the effects of global warming-related heat exposure on workers' health and productivity.* **Methods:** *Three separate searches, focused, respectively, on: i) heat-related illness (HRI), cardiovascular, respiratory and kidney diseases; ii) traumatic injuries; and iii) vector-borne diseases or vectors distribution, were conducted in PubMed. EMBASE was also consulted to retrieve relevant studies focused on the health effects of climate change. A fourth search strategy to assess the effects on work productivity was conducted both in PubMed and in the SCOPUS database.* **Results:** *A significant proportion of studies reported findings regarding the Mesoamerican nephropathy issue. This is a disease occurring especially among young and middle-aged male sugarcane workers, without conventional risk factors for chronic kidney disease. For injuries, there is a reversed U-shaped exposure-response relationship between Tmax and overall daily injury claims. Outdoor workers are at increased risk of vector-borne infectious diseases, as a positive correlation between higher air temperatures and current or future expansion of the habitat of vectors is being observed. As for productivity, agriculture and construction are the most studied sectors; a day with temperatures exceeding 32°C can reduce daily labour supply in exposed sectors by up to 14%.* **Conclusions:** *The present findings should inform development of further research and related health policies in the EU and beyond with regard to protecting working people from the effects of workplace heat during climate change.*

## RIASSUNTO

**«Cambiamento climatico ed effetti sulla salute e sulla produttività dei lavoratori: revisione della letteratura sugli effetti dell'esposizione al calore nei luoghi di lavoro».** **Introduzione:** *Negli ultimi decenni si è registrato un*

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Preliminary results of the study were presented at the 26th International Epidemiology in Occupational Health (EPICOH) Conference, Edinburgh, 29 August 2017.

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*importante aumento della temperatura atmosferica media e degli eventi meteorologici estremi. **Obiettivi:** Nell'ambito del Progetto Europeo HEAT-SHIELD abbiamo condotto una revisione sistematica allo scopo di valutare gli effetti del riscaldamento globale sulla salute e sulla produttività dei lavoratori. **Metodi:** Abbiamo utilizzato tre diverse strategie di ricerca, interrogando PubMed, per indagare, rispettivamente: i) il rischio di sviluppare malattie da calore, malattie cardiovascolari, respiratorie e renali; ii) il rischio di infortuni causati da eventi meteorologici estremi; iii) l'estendersi della presenza di vettori di malattie infettive nuove o di nuovo presenti. Inoltre abbiamo consultato anche il database EMBASE per valutare gli effetti dei cambiamenti climatici sulla salute dei lavoratori. Una quarta strategia, condotta sia su PubMed che su SCOPUS, ci ha permesso di esplorare il tema della produttività. **Risultati:** Di rilevante importanza è il problema della nefropatia mesoamericana, una condizione che interessa soprattutto i lavoratori maschi impiegati nella produzione della canna da zucchero in America Centrale. In generale, sembra esistere una relazione dose-risposta a forma di U rovesciata tra Tmax e infortuni. I lavoratori hanno un rischio aumentato di contrarre malattie infettive trasmesse da vettori poiché esiste una correlazione positiva tra temperature più elevate e l'espansione attuale o futura dell'habitat dei vettori. Per quanto riguarda la produttività, l'agricoltura e le costruzioni sono i settori più studiati; temperature superiori a 32°C possono ridurre la produttività fino al 14%. **Conclusioni:** I risultati della revisione potranno essere utili ai decisori politici per pianificare adeguatamente le azioni di salvaguardia della salute e della produttività dei lavoratori, messe a repentaglio da condizioni sempre più frequenti di disagio da caldo intenso e persistente.*

## BACKGROUND

The risks of heat exposure on human health are well known. The Italian physician Bernardino Ramazzini was probably the first, already in the 17<sup>th</sup> century, to report in his book “De Morbis Artificum Diatriba” on the ailments suffered by workers excessively exposed to heat stress. Bakers, he wrote: “...are afflicted by serious illnesses; in summer in particular, when they put the bread in the ovens and take it out, you can see them dripping with sweat.... I have observed that, in crowded cities, these workers fall ill more often than other workers”; as for soap-makers: “the ailments that afflict these workers are caused by the toil they endure day and night and the excessive heat from the fire that is constantly burning in the workshop. Indeed, it is so hot that they often have to go out for a moment to take a breath of fresh air....” (80).

At the beginning of the 20<sup>th</sup> century, J. S. Haldane reported the results of experiments evaluating the influence of high air temperatures on the health status of Cornish miners, and on subjects placed partly in incubating room at the Lister Institute in London, in a warmed room at the Physiological Laboratory in Oxford, and in a Turkish bath (39). He observed an increase in the pulse rate of 36 beats for each 1°C, the occurrence of hyperpnoea from 39.4°C and

a general feeling of exhaustion and discomfort when wet-bulb thermometer exceeds 25.5°C, when hard work becomes impracticable. In 1914 Luigi Carozzi wrote that when the “external temperature is higher than body temperature, and the air is saturated with moisture, the evaporation is hindered, and a heat-stroke may occur if internal temperature reaches 40.5°C” (17). Moreover, he underscored the effects on workers productivity, as he reported strikes in the textile and mining industries due to the harsh conditions posed by working in a hot, humid environment (16). A few decades later, in the 1960s, Cyril H. Wyndham described the health hazards and the effects on productivity posed by heat stress on South African gold mine workers (98). The occurrence of heat-related illness is maximum when the high temperatures are accompanied by high humidity levels, a condition which determines an impairment of the human thermoregulatory system.

Workers involved in moderate- or high-intensity activities in hot locations during the hot season are prone to heat-related health problems, as physical work activities create intra-body heat production, which adds to the environmental heat stress. A growing body of scientific evidence indicates that the exposure to excessively high heat levels is already resulting in excess morbidity and mortality in the general population, particularly among the elderly

(23, 93, 96, 97). Although workers in hot locations are also a vulnerable group for heat exposure and climate change, the impact of climate change on workers' health has not been extensively investigated. Guidelines and heat management systems to counteract increasing heat exposure in the occupational settings are still far from appropriately being implemented in at-risk regions (63). In addition, several studies have confirmed significant loss of productivity due to excessive heat exposure (53-55, 73).

With climate change, mean annual air temperatures are getting hotter in most parts of the world. Since thermometer-based observations began, the year 2015 and the period 2006-2015 were the warmest year and decade on record respectively. The global average surface temperature has risen at an average rate of 0.07°C per decade since 1901 (3). During the same period extreme weather events, such as heat waves, droughts, floods, cyclones and wildfires, have become more and more common, according to the findings from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), and impacts from recent climate-related extremes revealed, with very high confidence, "significant vulnerability and exposure of some ecosystems and many human systems to current climate variability" (91). For the 21st century, climate models have projected further increases of between 0.3 and 1.7°C for the lowest greenhouse gas emissions scenario adopted by the Intergovernmental Panel on Climate Change for its fifth Assessment Report (RCP2.6), and between 2.6 and 4.8°C for the highest emissions scenario (RCP8.5) (29). This will represent a public health issue, especially considering the ongoing process of the European working population ageing (the proportion of workers aged ≥50 years has markedly increased, from 24% in 2005 to 31% in 2015, when, for the first time in many years, the proportion of workers pertaining to this age group has surpassed that of the younger cohort (27)), which is resulting in more workers at greater risk of heat stress.

## OBJECTIVES

The present study has been conducted as part of HEAT-SHIELD, a project funded by the European Union under the Horizon 2020 Framework

Programme for Research and Innovation (<https://www.heat-shield.eu/>), dedicated to address the negative impact of increased workplace heat stress on the health and productivity of five strategic European industries: manufacturing, construction, transportation, tourism and agriculture. We performed a systematic review with the aim to summarize the epidemiological evidence of the effects of climate change, with a special focus on high temperatures and heat waves, on workers' health and productivity, in order to better inform health policies in the EU and beyond.

## METHODS

Brownson et al. distinguished three types of scientific evidence for public health practice (14); the aim of our review was to provide Brownson's type 1 scientific evidence, in that our objective was to identify size and severity of the existing relationship between heat related to climate change and workers' health and productivity.

To retrieve the relevant scientific literature on the effects of workplace heat on occupational health, it was decided to carry out three separate searches, one for each of the main health effects identified in a logical framework derived by the conceptual model produced by Schulte et al., with health outcomes varying depending on the exposure types (85, 86). These three search strategies were conducted in PubMed using pre-specified search terms and were focused on: i) heat-related illness (HRI), cardiovascular, respiratory and kidney diseases; ii) traumatic injuries and acute death; iii) vector-borne diseases or vectors distribution; they are shown in Appendix Table 1. To complement the search in PubMed, the EMBASE database was consulted, using a more concise search strategy [(‘climate change’/exp OR ‘climate change’) AND worker\* AND (‘health’/exp OR health OR injur\* OR disease\*)], to assess climate change effects on workers' health.

A fourth search strategy was conducted to retrieve the effects of climate change on work productivity. Since both PubMed and EMBASE databases are focused on biomedical topics, and generally do not include studies based solely on economics aspects, in this case it was decided to also conduct the search

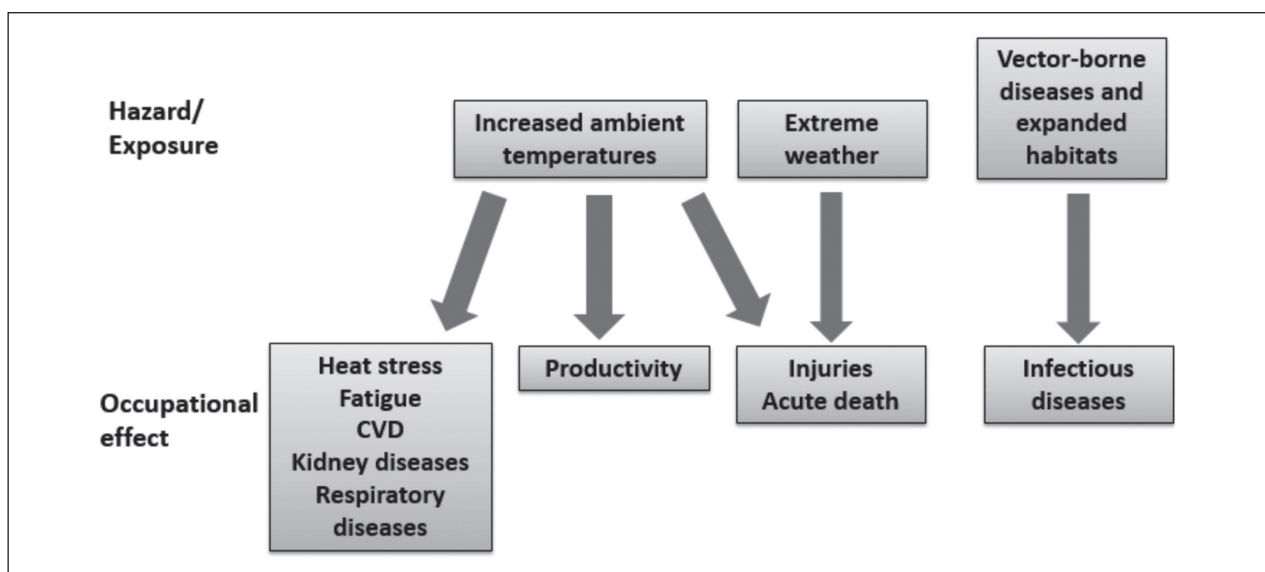
strategy in SCOPUS, a database which contains abstracts of academic journal articles with a broader focus (Appendix Table 2). In figure 1 the analytic framework developed to guide the selection of studies addressing the topics of interest is shown. An iterative process was used to build the search strategies, as there was no way for us to anticipate some concepts prior to encountering them while performing the review. Therefore, while the review of the first two topics of interest was carried out systematically, applying a modified versions of the PICO scheme (83), using a search syntax comprising three categories (i) *Exposure* ii) *Setting* ; iii) *Health outcome*), for the third and the fourth strategies it was decided to assess the distribution of hazards, and to opt for a scoping review, instead. During the review process, it was acknowledged that the increased risk of vector-borne infectious diseases for outdoor workers has not been studied extensively yet. The topic of productivity is mainly assessed by econometric studies, which was not the focus of our analysis. When building the search syntax, for prompt identification of studies conducted in the occupational setting, we made reference to the strings developed precisely for this purpose by Mattioli et al. (67).

Inclusion criteria were:

- Studies published from 01/01/2000 until 16/06/2017
- Studies focused on heat-related illness and injuries among workers or on workers' productivity with special attention to the construction and agricultural sectors.

Exclusion criteria:

- Experimental studies (e.g. studies involving subjects performing exercise in climatic chambers), under controlled conditions of heat stress
- Studies assessing the effects on subgroups whose exposure to heat is determined by industrial processes (e.g. workers of foundries or glass mills) or by environmental conditions potentially not related to climate change (e.g. underground miners, firefighters), unless the unfavourable environmental conditions described were explicitly correlated to the heat conditions that climate change brings
- Studies devoted solely to the analysis of the health effects of natural disasters (e.g. Hurricane Katrina)
- Studies assessing the impact of workplace heat on the production, rather than on workers' productivity at the individual level
- Editorials, commentaries, letters to the editor.



**Figure 1** - Logical framework used to guide the study selection. Modified from Schulte et al, 2009 (86) and Schulte et al, 2016 (85)

A two-step selection process was applied: relevant studies were selected by screening first the titles and then the abstracts; if the information in titles or abstracts was not sufficient to decide on inclusion or exclusion of the study, the full-text was retrieved and evaluated. The study selection process was done twice, independently by two researchers (ML and AB), to ensure that the predefined selection criteria were met. Disagreements about eligibility were resolved through discussion. Information on the selected studies was extracted by one reviewer based on the following items: source (first author and year of publication), study design, year of publication, country/region considered, study population, heat-exposure index employed, outcome evaluated and association measures employed (incidence rate ratio, odds ratio, proportions comparison) and main findings (Appendix Table 3 and Appendix Table 4).

## RESULTS

Using PubMed, the first search, focused on heat-related illness, cardiovascular, respiratory and kidney, diseases, resulted in 805 articles. Based on titles and abstracts, the full text of 132 potentially relevant articles was retrieved and reviewed, whereas 5 articles could not be retrieved. This resulted in 94 articles, and seven additional papers were included manually or using other strategies, for a total of 101 papers. Using EMBASE, three additional studies were retained: two studies (a case series and a narrative review, respectively) on the impact on kidney diseases in agricultural workers (18, 79) and one cross-sectional study focused on the mental health impact of recently observed patterns of climate change (26).

The second search, focused on traumatic injuries and acute death, resulted in 508 articles. Based on titles and abstracts, the full text of 54 potentially relevant articles was retrieved and reviewed. This resulted in 11 articles, and four additional papers were selected using the other strategies (total articles selected: 15).

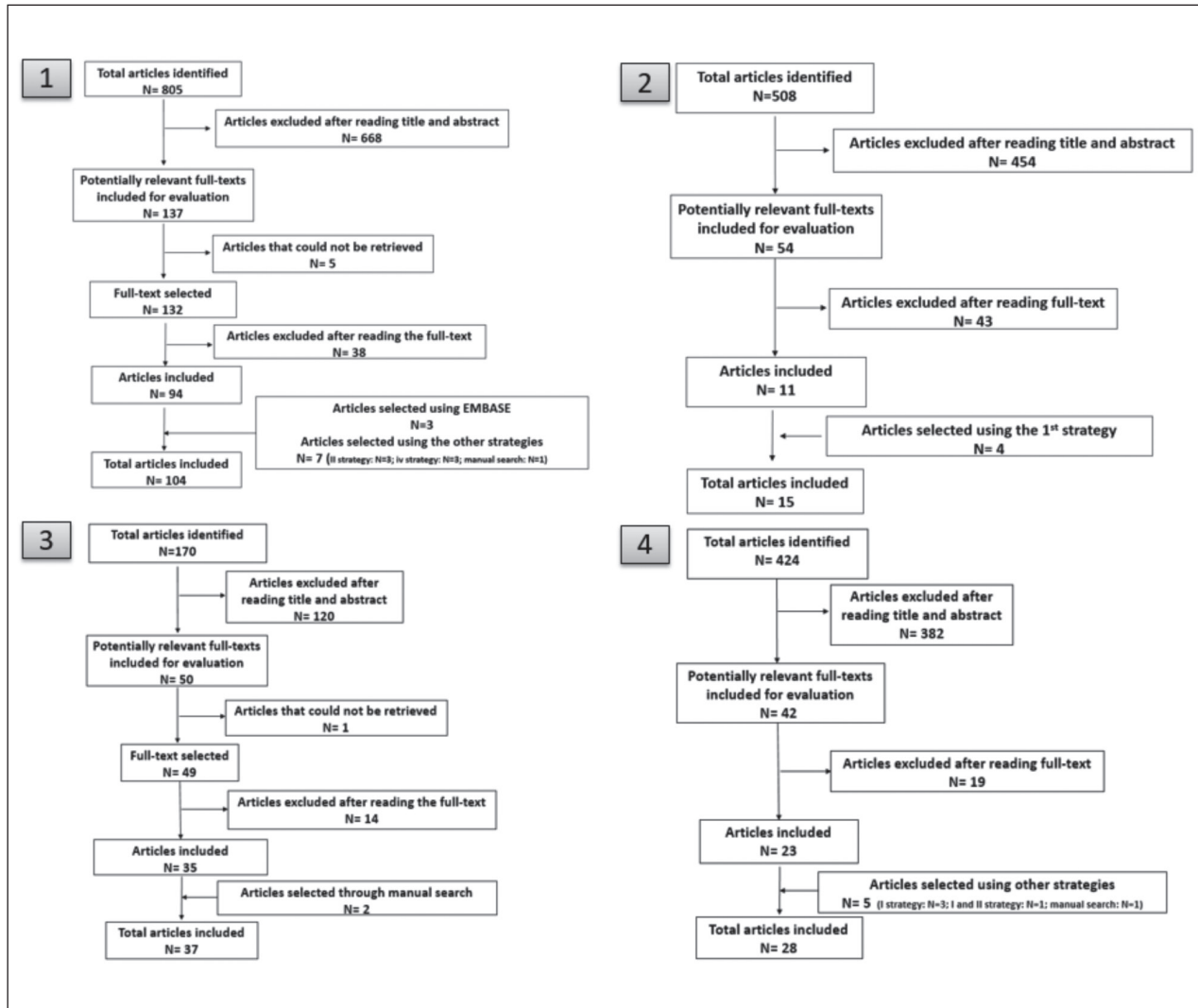
The third search, focused on vector-borne diseases or vector distribution, resulted in 170 articles. Based on titles and abstracts, the full text of 50 potentially relevant articles was retrieved and reviewed, whereas

1 study could not be retrieved. The review resulted in a total of 35 articles, and two additional papers were selected manually (total articles selected: 37).

The fourth search strategy, focused on workers' productivity, when conducted in PubMed, resulted in 424 articles. Based on titles and abstracts, the full text of 42 potentially relevant articles was retrieved and reviewed. The review resulted in a total of 23 articles, and five additional papers were selected (manually or using other strategies), for a total of 28 articles selected. When conducted in the SCOPUS database, the fourth strategy resulted in 380 articles. Based on titles and abstracts, the full text of 21 potentially relevant articles was retrieved and reviewed. This resulted in a total of 9 articles. In total, combining the search conducted in PubMed with the search in SCOPUS, 36 relevant studies focused on workers' productivity were retrieved. In figure 2 and figure 3 the flow charts of study selection are depicted.

In table 1 the studies selected are reported by study design. One fifth (N=39; 23.6%) were cross-sectional studies. Other common study designs were simulations based on climate driven models (22; 13.3%) (these represented the 28.8% of all relevant studies assessing the impact on vector-borne diseases or vector distribution and on labour productivity), within-group comparisons for the evaluation of physiological parameters such as body temperature, body weight change, heart rate, urinary specific gravity, and fluid intake at start, middle, and end of shift (mostly before-after studies without control group) (N=16; 9.7%), ecological (N=14; 8.5%) or case reports or case series (N=12; 7.3%). The studies employing more robust study design such as case-crossover, cohort or case-control, were relatively few (table 1). While in the years 2000-2004 no review was produced on any of the topics of interest, in the periods 2005-2008 and 2009-2012 two and ten narrative reviews, respectively, were published. In the last period examined, from 2013 until the first half of 2017, the number of reviews addressing the effects of climate change on workers' health and productivity increased, as 14 narrative reviews and 9 systematic reviews were published.

The majority of studies were conducted in North America (N=43; 26%), Asia (N=30; 18.2%),



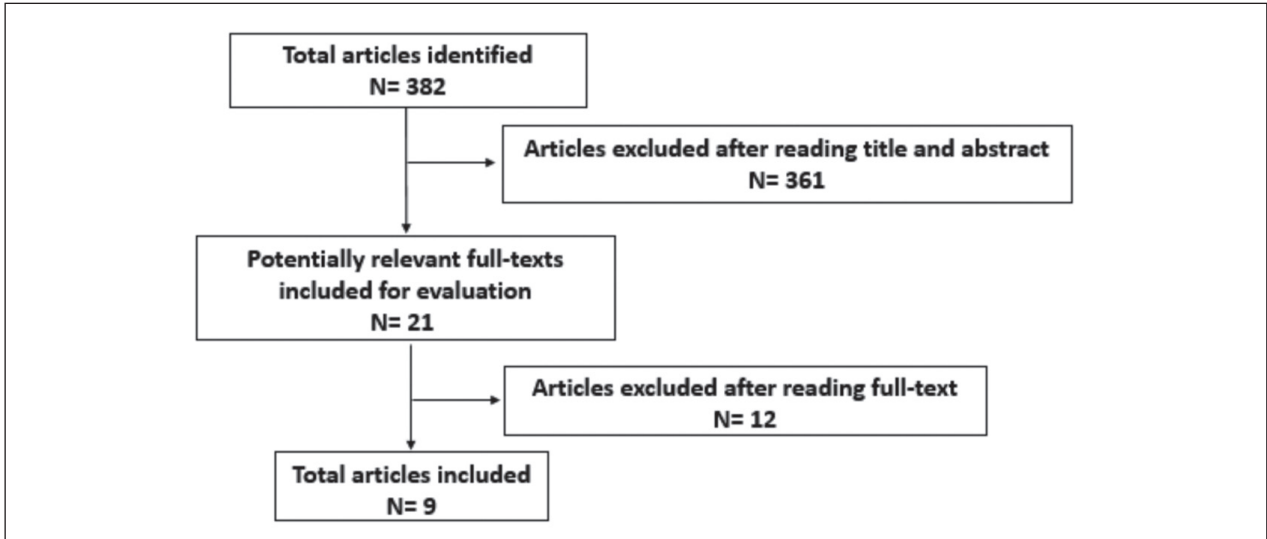
**Figure 2** - Publication selection process for the first three search strategies conducted in PubMed and EMBASE and the fourth in PubMed

Australia/New Zealand (N=20; 12.1%), Central America (N=14; 8.5%) or Europe (N=13; 7.9%) (figure 4).

In table 2 the number of selected publications is reported by specific outcome assessed per each search strategy. The first retrieved studies assessed mainly the impact on heat-related illness (N=60; 57.7%), physiological parameters (N=19; 18.3%), or kidney and urinary diseases (N=11; 10.6%). A significant proportion focused on the mental health impact (N=5; 4.8%) of recently observed patterns of

climate change. Only three studies assessed the effects on cardiovascular diseases, and only one evaluated the effects on acute respiratory problems.

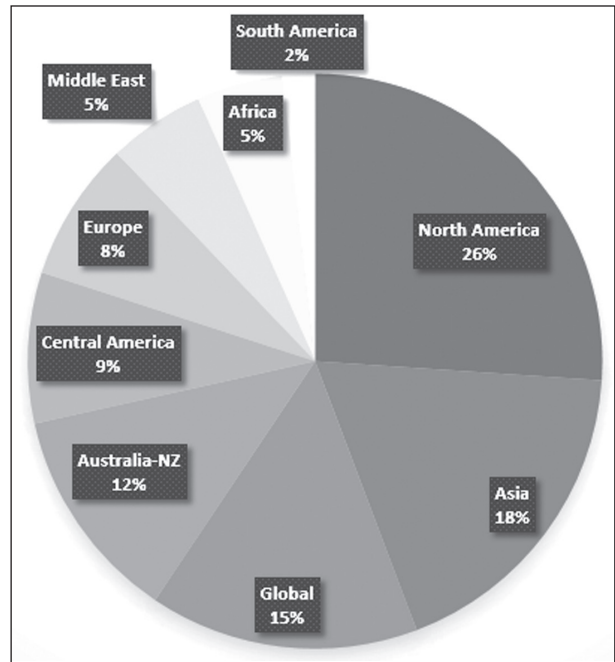
The majority of papers retrieved using the first, second and fourth strategies (80/129; N=62.0%) considered all groups of workers, especially when the source of data is represented by administrative databases, e.g. Adam-Poupart et al, 2015 (1), or Arbury et al, 2014 (7). Those working in agriculture/forestry were taken into consideration by over one fourth of studies included (N=37; 28.7%), and con-



**Figure 3** - Article selection process for the fourth search strategy in SCOPUS

**Table 1** - Selected papers reported by study design

Type of study design	N	%
Cross-sectional	39	23.6
Narrative/scoping review	26	15.8
Simulation based on climate driven model	22	13.3
Within-group comparison (e.g. physiological parameters monitoring)	16	9.7
Ecological	14	8.5
Case series/case report	12	7.3
Case surveillance	9	5.5
Systematic review	9	5.5
Case-crossover	5	3.0
Cohort	4	2.4
Time-series	3	1.8
Case-control	2	1.2
Cross-sectional with nested case-control analysis	1	0.6
Econometric model	1	0.6
Physiological parameters monitoring and productivity	1	0.6
Time series analysis/case-crossover	1	0.6



**Figure 4** - Geographical distribution of the selected papers

**First strategy**

struction workers were the target population of 14 publications (10.8%) (in table 3 the working groups targeted by the selected papers are shown by search strategy).

In total, as far as the first search strategy is concerned, the majority of papers selected (60/104) were focused on HRI, whereas nearly one fifth assessed the thermophysiological effect on workers. Studies

**Table 2** - Selected publications by specific outcome assessed using each search strategy

	N	%*
<b>Search strategy 1</b>		
Heat-related illness	60	57.7
Physiological parameters	19	18.3
Kidney diseases and urinary diseases	11	10.6
Mental health	5	4.8
Cardiovascular diseases	3	2.9
Heat-related cardiorespiratory symptoms	2	1.9
Human health	2	1.9
Allergies	1	1.0
Respiratory diseases	1	1.0
<b>Search strategy 2</b>		
Injuries	15	100.0
<b>Search strategy 3</b>		
Vector-borne diseases	17	45.9
Communicable diseases	12	32.4
Vectors distribution	8	21.6
<b>Search strategy 4</b>		
Productivity	36	100.0

\* The proportion of papers focusing on each specific outcome out of the total papers selected per each strategy is shown.

that evaluated HRI are mainly of two types. The first type (N=16) made use of data drawn from administrative databases (e.g. emergency department data (N=7) (32-34, 42-44, 82), workers' compensation claims (N=6) (2, 13, 37, 89, 99, 101), or hospital discharge records (N=3) (42-44)) and of a standard definition of heat-related illness, generally based on the International Classification of Diseases, Ninth or Tenth Revision, Clinical Modification (ICD9 CM codes 992 and ICD10 codes T67, V93.2, X30 and X32). Some of these studies (N=6) took the lag effect into account when analysing the health effects of heat (2, 13, 32, 37, 82, 89), however the lag times considered vary. The only two studies that analysed the effect of heat-waves are comprised in this group (99, 101). Six out of these 16 studies did not use heat exposure indicators to examine the association between heat or heat-waves and HRI, implicitly considering the causal relationship: in these cases the analysis was mainly focused on the different occupational categories, age and gender. In the 10 studies that used heat exposure indicators, seven used the

Daily Maximum Temperature, one used the Wet-Bulb Globe Temperature (WBGT), one the average annual summer temperature (Tmax) and the remaining study used the Apparent Temperature.

In the second type of study, the sources of data were represented by questionnaire surveys or interviews. The occurrence of HRI was generally based on the self-reported subjective symptoms in the workers. The list of symptoms examined varied; in some cases, particular attention was paid to the renal function, in other cases the questionnaire had open questions and the workers were free to report whichever symptom they needed to report and symptoms were *a posteriori* grouped by organ system. Two of these studies considered the lag effect (in both cases it was 0). Heat exposure indicators were used in 11 out of 18 studies: in eight studies the WBGT was measured, one used both the hourly humidity and the hourly maximum temperature, another both the mean maximum temperatures and the maximum heat index.

The physiological parameters generally assessed to examine heat stress and dehydration include body temperature, fluid intake, body weight change, urinary specific gravity and heart rate. A significant proportion of articles retrieved (N=11) dealt with genitourinary disorders, in particular kidney injury, chronic kidney disease and urolithiasis. Six out of 11 of these articles reported findings from studies conducted in Central America, where an increased incidence and prevalence of chronic kidney disease has been observed since the early 2000s, particularly in Nicaragua (18, 59, 78, 95), Costa Rica (20) and El Salvador (36, 74). The disease occurs especially among young and middle-aged male sugarcane workers, without conventional risk factors such as diabetes or hypertension. Since the aetiology is still unknown, the label "Chronic Kidney Disease of unknown aetiology" (CKDu) is being used in the scientific literature. Another label is "Mesoamerican nephropathy". The exposure to increased temperatures, dehydration and exposure to certain agrochemicals are thought to be the most important risk factors associated with its occurrence.

As for mental health, farmers seem to be at higher risk of developing depression, anxiety and other mental health problems, including suicide, on account of drought-related pressures (25, 26, 40, 41, 76).



**Table 3** - Working groups targeted by the selected papers by search strategy

	N	%
<b>First strategy</b>		
<i>Population group</i>		
Working population	32	30.8
Agriculture	28	26.9
General population, including working population	12	11.5
Construction	8	7.7
Armed force	5	4.8
Mining	4	3.8
Electrical	3	2.9
Firefighters	2	1.9
Manufacturing industry	2	1.9
Agriculture - Construction	1	1.0
Agriculture - Manufacturing industry	1	1.0
Construction - Traffic control	1	1.0
Outdoor workers	1	1.0
Other	4	3.8
<b>Second strategy</b>		
<i>Population group</i>		
Working population	9	64.3
Construction	2	14.3
Agriculture	1	7.1
General population, including working population	1	7.1
Manufacturing industry	1	7.1
Firefighters	1	7.1
<b>Third strategy</b>		
<i>Population group</i>		
<i>(excluding papers focusing on animals, vectors, Infectious agent)</i>		
General population, including working population	17	77.3
Agriculture	1	4.5
Humans, animals and vectors	1	4.5
Working population	1	4.5
School workers	1	4.5
Fish market workers	1	4.5
<b>Fourth strategy</b>		
<i>Population group</i>		
Working population	23	63.9
Agriculture	5	13.9
Outdoor workers	2	5.6
Manufacturing industry	2	5.6
Agriculture - Construction	1	2.8
Construction	1	2.8
Other	1	2.8
General population, including working population	1	2.8



at increased risk for schistosomiasis (10) and malaria (102) in China, dengue in Japan and Taiwan, leishmaniasis in Colombia (10) and West Nile Virus in Canada (103). The unusually warm winter of 2006–2007 supported vole population growth and contributed to the resurgence of leptospirosis in Germany among seasonal strawberry harvesters from Romania, Slovakia, and Poland (22). Electricity and pipeline utility workers are thought to be at increased risk of infection with Lyme Disease in the United States (9). Also in the Czech Republic the increasing trend of mean air temperatures found during the last three decades, most pronounced in the spring and summer months, was put in correlation with the highest activity of *Ixodes ricinus* ticks (21), and a simulation based on a climate driven model demonstrated that the habitat suitable for the distribution of *I. scapularis* in the Texas-Mexico transboundary region will remain relatively stable until 2050 (30).

The studies showed, in general, a positive correlation between higher air temperatures and current or future expansion of the habitat of vectors. Alimi et al. reported that altitude, annual precipitation and temperature are influential in both current and future models (4). Rift Valley fever outbreaks occurred after months of abnormal rainfall in Eastern and Southern Africa. Chikungunya outbreaks occurred in conditions of anomalous heat and drought in Eastern Africa. In Southeast Asia, such outbreaks were positively correlated with higher temperatures and rainfall (6).

Another infectious disease that is resurging on account of unusually warm weather or more frequent weather events (typhoon, droughts) is fascioliasis, a foodborne trematode infection caused by *Fasciola hepatica* and *Fasciola gigantica*. According to a simulation based on a climate driven model, the season suitable for the development of *Fasciola hepatica* in the environment will possibly be extended by up to four months in northern Europe; for southern Europe the risk will increase during the winter months (15). Tick-borne encephalitis virus is also on the rise (the northward expansion of *I. ricinus* has been well-documented in Scandinavia). Expansions have also been observed in African ticks (60), Crimean-Congo haemorrhagic fever (35) and

enteric diseases such as campylobacteriosis, salmonellosis, giardiasis and cryptosporidiosis (56, 57).

In Appendix Table 7 the papers selected using the third search strategy are listed.

#### Fourth strategy

Generally, work hours loss is used as a proxy for labour productivity loss. A day with temperatures exceeding 32°C can reduce daily labour supply in exposed sectors by up to 14% (45). In Australia workers carried out on average one hour less work per day when temperatures exceeded 37°C (compared with days in which temperature is below 30°C), as workers self-paced to maintain thermal comfort. Heat-related health risks increase when work is “externally paced” (41). Approximately one-third of baseline work productivity can be lost in physically demanding jobs when working at 40°C (87). In India, at WBGT > 26°C the hourly number of rice bundles collected by farm workers was reduced approximately 5% per °C of increased WBGT (84). In the USA, at daily maximum temperature > 29.4°C, workers in industries with high exposure to climate reduced daily time allocated to labour by as much as one hour. Almost all of the decrease in time allocated to labour happened at the end of the day (104). When subjects are dehydrated, productivity is reduced (12, 19, 52). Agriculture and construction are the most studied sectors (5, 12, 19, 58, 61, 69, 72, 84).

In Appendix Table 8 the papers selected using the fourth search strategy are listed.

#### DISCUSSION

The physiological mechanisms of extreme heat on human health have been well documented. Many experimental studies (e.g. climatic chambers, trials, workplace simulation studies) have proved that working in hot environments can increase the risk of injury. While those studies are at an individual level, there is lack of heat-injury evidence at a population level, where mostly ecological and observational studies have been conducted. After assessing the evidence from both individual and population level studies, we can confirm the heat-injury association.

Given the different characteristics of the data sources and of the heat exposure indicators used in the analysed studies it is not easy to further synthesize the results. However, the present findings confirm the relationship between high workplace heat levels and health effects in workers, even in younger age groups. The majority of studies employed a weak design (e.g. cross-sectional, case series) which does not allow to draw definitive conclusions. With regard to heat-related illness and injury, the data sources most used to conduct large, robust studies are workers compensations claims, emergency department data or hospital discharge records. Studies based on these data sources often employ heat indices such as the daily maximum temperature to assess the impact on workers' health. These are generally ecological studies, where the exposure is measured at the group, not at the individual level. On the contrary, the WBGT is the most frequently measured index employed by *ad hoc* studies. Studies conducted to assess the association between heat exposure and acute injuries either considered the impact of heat-waves, or of increased temperatures the day of the injury, and/or the climate conditions in the previous days, taking into account the lag effect. The effects of high temperatures are generally assessed, whereas that of heat-waves currently appear to be the most neglected.

The EU strategy on adaptation to climate change supports action aimed at making Europe more climate-resilient by promoting greater coordination and information-sharing (28). Meteorological early warning systems, timely public and medical advice, and ensuring that health care and social systems are ready to act are among the action recommended by the Health Action Plan, a product of EuroHEAT project on improving public health responses to heat-waves and extreme weather events, co-funded by the European Commission (66). Almost all countries have their own heat stress management guidelines in place. Currently, heat prevention policies mainly focus on the impact of extreme heat on occupational health. However, heat appears to be a silent killer. As a matter of fact, evidence has shown that the heat-injury relationship is a reversed U-shaped curve: work-related injuries start to increase with the increase of maximum temperature when temperatures are still not too high. Furthermore, con-

sidering that heat stress is affected by external heat (weather-related heat and machine-generated heat), as well as by internal heat (physical activity) and clothing, some workers may still be at high risk of injury even under mild heat stress conditions. The evidence we found regarding the health effects on construction workers is surprisingly scarce, and we have not found studies targeting susceptible workers, such as those affected by cardiovascular or respiratory chronic diseases, who are particularly at risk of suffering the worst consequences.

The kidney disease affects also countries and occupations not currently categorised among those affected by the problem of the CKDu, suggesting that future research continues to search for causes and evaluate the condition particularly among outdoor workers directly exposed to sunlight in the summer months, even in other areas of the world (e.g. seasonal tomato harvesters in Italy) currently still not considered at-risk.

Since the evidence on the effects of climate change on vector-borne infectious diseases is currently still very scarce with reference to the working population, it was decided to focus the analysis on the increased risk of infections in general, and to also consider as possible effect of climate change the altered distribution of vectors. In this case, the conclusion that outdoor workers will experience an increased risk of developing this type of health outcomes was made by deductive reasoning, given the present and future expansion of vectors' habitats. A recent study suggested that climate change and the increasing frequency of extreme events such as desert dust storms are significantly changing the microbial communities of our soils, moving entire microbial communities (bacteria and fungi), including organisms which are extremely resistant and able to survive in different environments far away from their origins (94). A recent overview of current climate change-infectious diseases research indicated that climate change contribution results may be underestimated from the failure to account for co-factors, such as the human-induced snail elimination in the case of schistosomiasis and chemotherapy effects (62). Furthermore, climate change may also affect the pathogens' life cycle stages within vectors, the incubation period duration, as well as vector-human

interactions. In the meantime, while we were writing this paper, the first potential cases of occupational malaria among migrant seasonal farmers were being notified in Italy (105).

For the assessment of the impact on vector-borne diseases or vector distribution, and on labour productivity, the evidence is largely based on climate driven model simulations. This means that to draw definitive conclusions we must rely on the precision of baseline estimates. In addition to the reduction of afternoon working hours loss in hot days and the reduction of work efficiency, days lost due to heat-related illnesses/injuries result in productivity losses as well.

The present study has several limitations that need to be commented on. The first is that mortality data, on which health surveillance systems are often based, are used to assess the impact of heat on population health. However, in the working population the increased mortality risk is only a small part of the health impact. The second limitation is that important health outcomes (e.g. mental health problems) were not assessed, or were only briefly mentioned. Finally, the topic of productivity loss was not exhaustively treated: the effects were measured as working hours loss, but the decreased production output and the quality of the products were not assessed.

Nonetheless, the results of our systematic review are helpful to inform continued search and development health policies, to protect workers from current and future heat exposures as climate change increases the problems. The challenges from heat exposure to the health and productivity of workers are significant problems already in tropical areas, and will become more and more common also in EU countries. The workforce in Italy is particularly at risk given the country's geographic and meteorological conditions; however, no specific study has been carried out so far, even if many heat-related deaths, mainly regarding agricultural and construction workers, appeared in the news in recent years (particularly in 2015) (48). Within the HEAT-SHIELD Project, the intention in the near future is to carry out studies to assess the effectiveness of several public health interventions in mitigating the health effects of climate change, and to assessing the adaptation and translation of such interventions in Italy and other Mediterranean countries.

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