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Heat-related productivity loss: benefits derived by working in the shade or work-time shifting

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Abstract

Purpose – Agricultural workers represent an important part of the population exposed to high heat-related health and productivity risks. This study aims to estimate the heat-related productivity loss (PL) for moderate work activities in sun and shady areas and evaluating the economic cost locally in an Italian farm and generally in the whole province of Florence. Benefits deriving by working in the shade or work-time shifting were provided. Comparisons between PL estimated in Mediterranean (Florence, Italy) and subtropical (Guangzhou, China) areas were also carried out.

Design/methodology/approach – Meteorological data were collected during summers 2017–2018 through a station installed in a farm in the province of Florence and by two World Meteorological Organization

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(WMO)-certified meteorological stations located at the Florence and Guangzhou airports. These data were used to calculate the wet-bulb globe temperature and to estimate the hourly PL and the economic cost during the typical working time (from 8 a.m. to 5 p.m.) and by advancing of 1 h and 2 h the working time. Significant differences were calculated through nonparametric tests.

Findings – The hourly PL and the related economic cost significantly decreased ($p < 0.05$) by working in the shade and by work-time shifting. Higher PL values were observed in Guangzhou than in Florence. The decrease of PL observed by work-time shifting was greater in Florence than in Guangzhou.

Originality/value – Useful information to plan suitable heat-related prevention strategies to counteract the effects of heat in the workplace are provided. These findings are essential to quantify the beneficial effects due to the implementation of specific heat-related adaptation measures to counter the impending effects of climate change.

Keywords Climate change, Heat stress, WBGT, Black globe temperature, Bio-economy

Paper type Research paper

1. Introduction

Outdoor workers represent an important part of the population potentially at high risk of external heat exposure and related health effects for many easily understandable reasons. They have to work regardless of weather conditions, often involved in intense physical activities, even working for many hours to direct sun exposure (with no shade) or artificial radiant heat and, in several cases, wearing heavy personal protective clothing and equipment (Gao *et al.*, 2018) that limit the body heat loss. The advanced working age and the potential interaction between heat and chemical substances (i.e. pesticides and fertilizers) used in agricultural activities represent other important heat-related vulnerability factors. For these reasons, policy interventions and forward planning to protect workers from heat stress are urgently needed.

Today, the wet-bulb globe temperature (WBGT) index (Minard *et al.*, 1957) is the international reference among heat stress indices for workplace applications, and it is used as an international standard (NIOSH, 2016; ISO-7243, 2017).

In general, the combination of external heat exposure, additional heat sources in the workplace and internal heat production can cause heat strain that may result in clinical damages to organ functions, physiological changes and psychological changes (Kjellstrom *et al.*, 2016). This situation may lead to diminished occupational performance capacity through reducing working endurance, vision, coordination and concentration (Parsons, 2014), in this way reducing vigilance and potentially causing more mistakes while working, with a general performance degradation and a consequent increase of injuries (Binazzi *et al.*, 2019).

During extensive heat conditions, workers take more frequent and longer rests to prevent heat strain, which may cause significant reduction in labour productivity and individual economic output (Jackson and Rosenberg, 2010; Kjellstrom *et al.*, 2016). In a recent study (Day *et al.*, 2019), the authors reported that the heat-related PL is one of the most prominent “market impact” in studies on the economic effects of climate change. However, field studies that have tried to quantify the economic impact of heat stress based on worker’s productivity are still very uncommon (Budhathoki and Zander, 2019; Vanos *et al.*, 2019), and there is no agreement among economists on which methods for estimations of these heat impacts would ensure reliability and validity for future projections (Kjellstrom *et al.*, 2019a).

The estimation of labour PL due to heat stress is currently possible by using the international ISO-7243 standard (NIOSH, 2016; ISO-7243, 2017) or the most recent risk function based on the few available epidemiological studies (Kjellstrom *et al.*, 2018).

Primary sectors of the economy are the occupational environments most affected by heat stress. Ensuring a reasonable standard of living for farm workers represents one of the general objectives for agricultural policy already set in the Treaty of Rome, signed in 1957 (Nilsson and Nilsson, 2005). Nevertheless, workers and their productivity are often overlooked in discussion about the heat effects (Kjellstrom *et al.*, 2016).

At European level, a great contribution on this topic is provided by the European project “Integrated inter-sector framework to increase the thermal resilience of European workers in the context of global warming" (HEAT-SHIELD) (https://www.heat-shield.eu/) that aims to develop solutions to protect the health and productivity in workplaces from excessive heat in the context of climate change. At international level, very important are the signals deriving from the study of heat stress conditions that are currently affecting workers living in countries located in tropical and subtropical areas. These countries are already experiencing severe and persistent heat stress conditions and that in the near future, due to climate change, may quickly affect also countries at temperate latitudes, which will require urgent and efficient adaptation measures. For this reason, some HEAT-SHIELD's partners are actively collaborating with Chinese colleagues studying the heat-related worker's health and productivity also in sub-tropical areas. At European level, the Italian HEAT-SHIELD's partners were involved during last summers in case studies collecting detailed micrometeorological data in some local farms with the aim of obtaining information on the effective heat stress conditions to which workers are exposed during typical working hours.

Italy is the third European country in terms of agriculture workforce, only after Romania and Poland (https://ec.europa.eu/agriculture/sites/agriculture/files/rural-area-economics/briefs/pdf/08_en.pdf). In 2017, almost 900,000 workers were employed in the Italian agricultural sector, which represents 3.8% of the national workforce and about 9% of the EU-28 agricultural workforce (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Farmers_in_the_EU_-_statistics). This labour force contributed about 2% to the gross value added produced by the Italian economy. The agricultural injury frequency in Italy in 2017 was about 5.5% (about 34,000 injuries) of the total national occupational injuries, and specific countermeasures preventing heat-related illness, such as worker breaks to access to cool potable water and to shade, wearing ventilated clothes and work-time shifting, are of primary necessity (Jackson and Rosenberg, 2010).

This study aims to estimate the potential hourly PL of workers for moderate (300 W) work activities in sun and shady areas assessed by using detailed micrometeorological data collected in the field during the summers 2017–2018, specifically in an Italian farm located in the province of Florence (Tuscany). The economic cost of the heat-related illness prevention through worker breaks under the situation in which the work-time recommendation is strictly followed was calculated. As this study is based on the hypotheses that the typical expected PL during the hottest season might be reduced by working in the shade or shifting the working time, these possible benefits were quantified. In addition, heat-related PL of workers were also estimated for the same periods by using data from two WMO-certified meteorological stations located at the Florence (Italy) and Guangzhou (China) airports, and PL comparisons between these two areas were provided. This type of investigation is potentially very useful because the Chinese subtropical location is already experiencing severe and persistent heat stress conditions during summer. For this reason, in-depth knowledge of the effect of heat stress on PL in the Chinese location can help to plan heat-related occupational prevention strategies also in Mediterranean areas to counteract the increasing heat stress forecasted in the next years due to the global warming.

2. Methods

2.1 Meteorological data and area of study

Local meteorological data were collected during summers (June 15 to September 15) 2017 and 2018 through a local meteorological station (HOBO U30 NRC) installed in a farm of wine and honey production in the province of Florence (Tuscany region, Central Italy) participating in case studies foreseen in the European HEAT-SHIELD project. Data on solar radiation (Wm^{-2}), barometric pressure (hPa), air temperature (°C), relative humidity (%), wind speed (ms^{-1}), wind direction (°) and black globe temperature (°C) were recorded at about 2 m above the ground during the whole study period with a time interval of 15 min. The black globe temperature was measured inside a 150 mm diameter black globe and validated by the comparison with a standard WBGT heat stress monitor instrument (Bruel and Kjaer, type 1,219).

For the same period and by using the NOAA Global Hourly Data Web platform of Climate Data Online (https://www.ncdc.noaa.gov/cdo-web/), hourly meteorological data of wind speed, air and dew point temperatures were collected from to WMO-certified meteorological stations located at the Florence (Italy) and Guangzhou (China) airports. The wind speed values measured at about 10 m were scaled up to 2 m according to the formula used in the study by Bröde *et al.* (2012). Solar radiation data were obtained by using daily solar radiation data downloaded by the Power Single Point Data Access web platform of NASA (https://power.larc.nasa.gov/data-access-viewer/) and then converted to hourly solar radiation by using the solar position and radiation calculator developed and maintained by the Washington State Department of Ecology (solrad.xls, version 1.0). This latter represents a translation of NOAA’s JavaScript solar position calculator (http://www.srrb.noaa.gov/highlights/sunrise/azel.html).

Florence (lat. 43°46′17″N; long. 11°15′15″E, average altitude of 50 m a.s.l.) was included in this study because it is one of the warmest European cities under study within the HEAT-SHIELD project. According to the Köppen climate classification scheme (Rubel and Kottek, 2010), Florence is characterized by a borderline humid subtropical (Cfa) and Mediterranean (Csa) climate, with a moderate influence from the sea (the city is located 80 km from the Tyrrhenian Sea). Summers are hot, and the warmest months are July and August: mean monthly temperature of about 24 ℃ and a monthly mean dew point of about 17 ℃ (monthly mean values of relative humidity about 65%).

The Chinese city region of Guangzhou (one of the biggest Chinese cities) was selected because it is located in a subtropical area (23°12’N, 113°29’E, 72 m) with higher monthly mean air and dew point temperatures that easily create stressful sultry conditions during summer months. Guangzhou is located in a subtropical monsoon climate region (Köppen Cfa) usually experiencing long summers with high temperatures also associated with very high humidity levels. In particular, the warmest months are July and August, with monthly mean temperatures above 28 ℃ and a mean dew point temperature slightly above 24 ℃ (monthly mean values of relative humidity close to 80%). Close to Guangzhou city, there are also major farming areas similar to the situation in Florence.

2.2 Heat stress index calculation

Heat stress conditions accounting for sun exposure and full shade situations were calculated in the locations under study by the WBGT index. WBGT was originally developed by US military ergonomists in the 1950s (Minard *et al.*, 1957) and is currently widely used and internationally recognized (NIOSH, 2016; ISO-7243, 2017) as a method for assessing heat stress conditions in occupational fields. WBGT considers the combination of several important microclimate variables, such as the natural wet-bulb temperature (T_{nwb}, ℃), the black globe temperature (T_g, ℃) and the dry-bulb temperature (T_a, ℃), in this way estimating heat stress exposure in the sun and in the shade. The WBGT_sun (in conditions of direct short-wave radiation) equation was used (Eqn 1) because most of the work activities carried out in the farm involved in this study were outdoors.

$$\text{WBGT\_sun}(°C) = 0.7T_{\text{nwb}} + 0.2T_g + 0.1T_a \tag{1}$$

However, with the aim to understand the possible contribution that would be made working in shadow conditions, the WBGT_shade (no direct short-wave radiation) was also calculated (Eqn 2).

$$\text{WBGT\_shade}(℃) = 0.7T_{\text{nwb}} + 0.3T_g \tag{2}$$

As seen from Eqns 1 and 2, T_{nwb} is the largest component (70%) of WBGT. T_{nwb} is a combination of air temperature and humidity, but it is also influenced by heat radiation and wind speed. T_{nwb} was calculated by the Liljegren method (Liljegren *et al.*, 2008), implemented in the heat stress calculation tool provided by the Climate Chip (Climate Change Health Impact and Prevention) Web platform (http://www.climatechip.org/). Today, WBGT represents the most commonly used heat stress index for workplace applications (Kjellstrom *et al.*, 2016; Takakura *et al.*, 2017) because it also includes recommendation for intrahourly rest/work cycles at different metabolic rates clearly specified by ACGIH (2015) and the international standard (ISO-7243, 2017).

2.3 Productivity loss (PL) estimation

The hourly PL due to heat stress was estimated for workers involved in moderate work activities (300 W) exposed in the sun and in the shade by using two risk functions: (1) based on ISO-7243 (NIOSH, 2016; ISO-7243, 2017); (2) based on epidemiological data (Kjellstrom *et al.*, 2018).

The ISO-7243 (2017) indicates, for various work intensity levels, the WBGT thresholds above which a worker should reduce her/his metabolic rate by performing several minutes of rest within an hour's work in order to avoid that the core body temperature rises above 38 °C. This situation avoids risks to the worker's health but also creates PL. In this study, the ISO-7243 risk function for moderate work activities (300 W) was used. These calculated breaks assume that the worker and their employers implement the ISO recommendations.

The other risk function was developed by Kjellstrom *et al.* (2018) reviewing the few epidemiological data sets currently available (Wyndham, 1969; Sahu *et al.*, 2013) for moderate work activities (metabolic rate of 300 W).

The shape of both risk functions (Figure 1) followed a cumulative normal distribution (Eqn 3).

$$\mathrm{PL}(\%), y = 0.5\left[1 + \mathrm{erf}\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right] \tag{3}$$

where μ and s represent the mean and standard deviation, respectively, of the associated normal distribution.

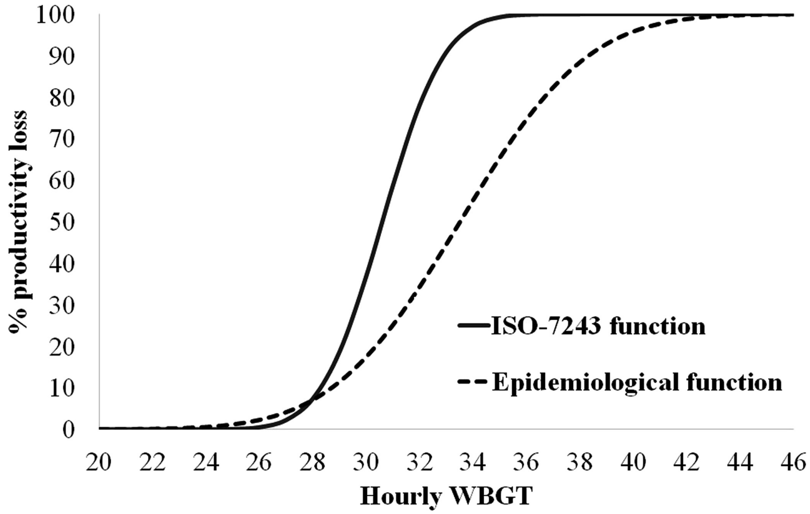

Figure 1. Estimated exposure-response relationships for reduced hourly work capacity (labour productivity) in jobs at 300 W intensity based on international standard (ISO-7243 function) and epidemiological data (Epidemiological function).

These risk functions directly convert a WBGT value in a percentage of PL (y is a value ranging from 0 to 100%) estimated considering that a worker reduces the work intensity with increasing heat stress, avoiding clinical problems (Kjellstrom *et al.*, 2018).

The daily mean PL was estimated accounting for workers exposed in the sun and in the shade by using meteorological data collected in the localities under study in three working times (WTs):

1. WT_{8-17}: from 8 a.m. to 5 p.m. (with 1 h break from 12 a.m. to 1 p.m.) that represents the typical daily working hours of workers employed in the farm participating in the HEAT-SHIELD case study;
2. WT_{7-16}: from 7 a.m. to 4 p.m. (with 1 h break from 12 a.m. to 1 p.m.);
3. WT_{6-15}: from 6 a.m. to 3 p.m. (with 1 h break from 11 a.m. to 12 a.m.).

2.4 Economic cost estimation

The economic cost estimation was carried out on a local scale considering the exact number of agricultural workers involved in the farm (selected to participate in case studies of the HEAT-SHIELD project) located in a rural area of the province of Florence and on a larger scale estimating the annual work unit (AWU) involved in the wine sector in the whole province of Florence.

The Florence farm involved in this study included 18 workers engaged in outdoor activities addressed to viticulture and committed for 5 days a week (from Monday to Friday). After the administration of a self-assessment questionnaire on the impact heat on worker’s activities, almost 80% of these workers (14 workers) declared that the heat, and especially the heat wave, has an impact resulting in a perceived PL. In particular, a perceived PL of about 10% declared by 7 workers; PL between 10 and 30% stated by 6 workers; even more than 30% declared by 1 worker.

According to the local territorial collective labour agreement for permanent employers (effective from May 1st, 2017), 14 workers were classified as “common workers”, with a gross monthly salary of €1,305.90 (daily salary of €50.2), and 4 were classified as “qualified workers”, with a gross monthly salary of €1,459.14 (daily salary of €56.1). Then, the economic cost due to PL of workers was calculated by multiplying the daily salary of all workers by the PL estimated by the risk functions (Eqn 4).

$$\text{Economic cost}(€) = \text{Workers salary}(€) x \text{PL}(\%) \tag{4}$$

Taking an example, considering a day with a 5% heat-related PL and the daily salary of 14 common workers (€50.2 × 14 workers × 5%) and the 4 qualified workers (€56.1 × 4 workers × 5%), the estimated daily economic cost would be €46.4.

Therefore, the economic impact estimated in this study is the economic cost of heat-related illness prevention through worker breaks under the situation in which the work-time recommendation is strictly followed. The quantitative economic estimation used in this study was similar to that already published in a previous case study carried out in Canada (Vanos *et al.*, 2019).

With the aim of extending the economic cost estimation to the whole province of Florence, the AWU indicator, already used in previous bioeconomic studies on agriculture (Spička and Smutka, 2014; Mantino, 2017; Nowak *et al.*, 2019) was calculated. As defined by the European Commission (https://ec.europa.eu/knowledge4policy/glossary/annual-work-unit_en), 1 AWU corresponds to the work performed by one person who is occupied on an agricultural holding on a full-time basis (about 1,800 h). In this study, AWU was calculated by using the number of hectares of vineyards in the province of Florence (just over 16,000 hectares in 2017) obtained by consulting the statistical database on agriculture of the Tuscany Region (https://www.regione.toscana.it/statistiche/pubblicazioni-statistiche/agricoltura) and the annual work (number of hours) necessary to manage 1 hectare of vineyard (270 h per hectare) obtained by consulting the hectare culture tables which allow to determine the required labour needs per hectare in the various crops (Decree of March 5, 2001, of the Italian Department of Agriculture and Forestry published on GURS N. 39 of August 3, 2001: Determination of the work requirement needed per hectare of crop). The economic cost estimation for the whole province of Florence was then obtained multiplying the AWU by the PL (hours of work lost during the summers) and by the hourly salary of a common agricultural worker.

2.5 Statistical analyses

Descriptive statistics of measured meteorological variables and WBGT during the three different working times ($WT_{8–17}$, $WT_{7–16}$, $WT_{6–15}$) were provided for the local Italian farm and the two WMO-certified meteorological stations located at the airports of Florence (Italy) and Guangzhou (China).

Hourly PL values for workers exposed in the sun and in the shade during the three different daily working times and the related economic costs were estimated during the whole summer period at the Italian farm. With the aim to increase the sample size, the economic cost was also estimated for the whole province of Florence. Significant differences between PL in the sun and shady areas and among different working times were calculated through the nonparametric Mann–Whitney and Kruskal–Wallis tests.

For the same period, similar analyses were also carried out assuming heat stress exposure of workers based on microclimate conditions recorded at the Italian (Florence) and Chinese (Guangzhou) airport meteorological stations. In this way, PL differences between the two cities were shown, and the possible benefits deriving by working in shady conditions or shifting the working time were quantified.

The computations were carried out by using the IBM SPSS Statistics, version 25.0.

3. Results

3.1 Productivity loss and economic cost estimation

Based on microclimatic and heat stress conditions (Table 1) monitored at the farm during the typical working time ($WT_{8–17}$) and the two modified working times ($WT_{7–16}$ and $WT_{6–15}$), the average values of most microclimate variables significantly decreased going from $WT_{8–17}$ to $WT_{6–15}$. The only exception was the relative humidity that instead revealed an opposite behaviour, thus showing significant increases progressively anticipating the working time. Even the average values of WBGT_sun and WBGT_shade revealed significant decreases by anticipating the working time of 1 h and above all 2 h: WBGT_sun and WBGT_shade decreased by about 10% and 8%, respectively, going from the typical working time ($WT_{8–17}$) to $WT_{6–15}$.

The PL in the shade was significantly lower (more than 80% lower) than the PL in the sun (Figures 2 and 3). The highest PL values were estimated with the ISO-7243 function.

Table 1. Hourly average microclimate variables and WBGT values in the sun (WBGT_sun) and in the shade (WBGT_shade) monitored at the farm during the summer 2017–2018 at different working times (WT_{8-17}, WT_{7-16} and WT_{6-15})

Variables	$WT_{8–17}$	$WT_{7–16}$	$WT_{6–15}$	p
T_a (°C)	27.0 (±5.6)	25.4 (±6.1)	23.8 (±6.3)	<0.001
RH (%)	51.6 (±20)	57 (±21.5)	61.9 (±22)	<0.001
V (ms^{-1})	1.0 (±0.9)	0.9 (±0.9)	0.8 (±0.8)	<0.001
T_g (°C)	36.6 (±8.3)	33.9 (±9.8)	31.1 (±10.8)	<0.001
WBGT_sun (°C)	24.7 (±3.7)	23.5 (±4.5)	22.2 (±5.1)	<0.001
WBGT_shade (°C)	21.8 (±3.1)	20.9 (±3.6)	20.0 (±3.9)	<0.001

Note(s): In round brackets, the standard deviation is indicated. Significant variations among the three different working times is calculated through the non-parametric Kruskal–Wallis test

In addition, higher statistically significant PL values were observed during the typical working time ($WT_{8–17}$) rather than PL observed by 1 h ($WT_{7–16}$) or 2 h ($WT_{6–15}$) work-time shifting (Figures 2 and 3). In particular, PL in the sun decreased by 18% if the workers started working 1 h earlier (starting to work at 7 a.m.) and even by 33% if they shifted the working time by 2 h (starting at 6 a.m.) respect to the typical working time (starting at 8 a.m.).

The hourly economic cost (considering the 18 workers involved in the Florentine farm) due to the PL in the sun during the typical working time ranged between €5.7 (PL based on the epidemiological function) and €8.0 (PL based on the ISO-7243 function). This impact was significantly reduced by anticipating of 1 h and especially 2 h the working time. In this latter case, the hourly economic cost ranged between €3.8 and €5.4 for PL calculated based on the epidemiological and the ISO-7243 function, respectively. The hourly economic cost due to the PL of workers engaged in shady conditions was significantly lower than the PL in the sun: it was always lower than €1.0 and even lower than €0.5 during WT_{6-15} regardless of the PL function used.

The total heat-related economic costs (the sum of both summers 2017 and 2018) in the farm estimated during $WT_{8–17}$ by using the epidemiological function ranged between about €6,000 for the 18 workers exposed to the sun (the economic cost could be even higher if PL

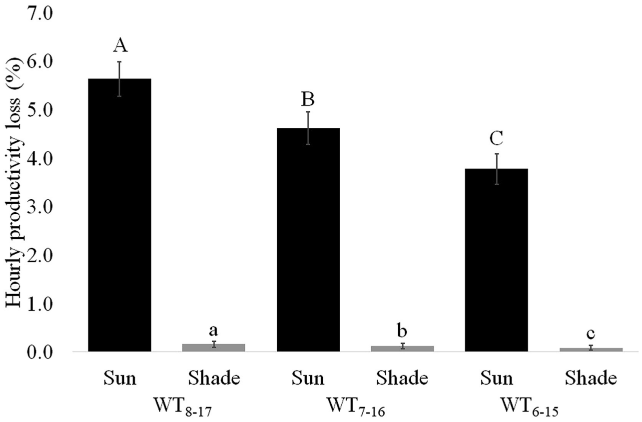

Figure 2.
Hourly productivity loss estimated by the ISO-7243 function in the sun and in the shade during different working times in an Italian farm (summers 2017 and 2018). Different letters indicate statistically significant differences ($p < 0.05$) between working times.

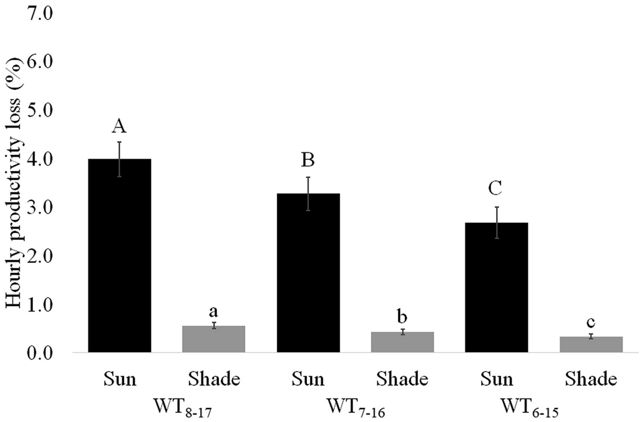

Figure 3.
Hourly productivity loss estimated by the epidemiological function in the sun and in the shade during different working times in an Italian farm (summers 2017 and 2018). Different letters indicate statistically significant differences ($p< 0.05$) between working times.

estimated with the ISO-7243 function was considered) and about €830 for workers working in shady conditions (Figure 4).

The economic cost estimation for the whole province of Florence revealed a labour input (in terms of persons working fulltime) of about 2,500 workers involved in the wine sector and the estimated total (the sum of both summers 2017 and 2018) heat-related economic cost ranged between about €800,000 for workers exposed to the sun during $WT_{8–17}$ and about €542,000 during $WT_{6–15}$ (a reduction of about 33%). The economic cost was significantly ($p < 0.01$) lower for workers working in the shade (about €113,000 for $WT_{8–17}$ vs. about €68,000 for $WT_{6–15}$).

3.2 Productivity loss differences based on meteorological data recorded at the Florence and Guangzhou airports

The hourly PL estimated during the typical working time ($WT_{8–17}$) by using the Florence airport meteorological data was lower than the PL estimated by using the local farm meteorological data (Figure 5). This result depends above all on significantly lower humidity levels at the airport (about 40% at the airport vs. about 50% at the farm) and higher wind intensities (about 2 ms^{-1} at the airport vs. about 1 ms^{-1} at the farm) than those observed at the farm, although the average air temperature at the city airport (28.4 °C ± 4.6) was about 1.4 °C higher than the rural one recorded at the farm, The relationships between the Italian (Florence) and Chinese (Guangzhou) PL estimated in the sun and in the shade calculated by using the airport meteorological data (Table 2) revealed substantial higher values in Guangzhou compared to Florence. The PL values estimated in the sun in Guangzhou were 7.3, 8.2 and 8.3 times higher than the PL values estimated in Florence when $WT_{8–17}$, $WT_{7–16}$ and $WT_{6–15}$ were considered, respectively. These relationships were even greater when PL values estimated in shady conditions were considered (Table 2).

The hourly PL for workers exposed to the sun in the Chinese location was always higher than 15%, even changing the working time (Table 2): the average WBGT value always remains next to 29 °C even anticipating working time by 2 h. The hourly PL in the sun decreased by 2.2% in Guangzhou and 12% in Florence if the workers started working 1 h earlier ($WT_{7–16}$) and even by 9.3% in Guangzhou and 20.2% in Florence if they shifted the working time by 2 h ($WT_{6–15}$), respect to the typical working time ($WT_{8–17}$).

On the other hand, the situation improves considerably in both cities if working in the shade was considered. In this case, in fact, the hourly PL in all working times ranged between

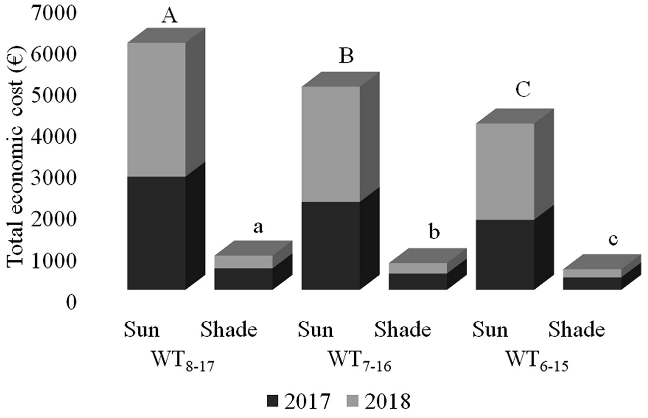

Figure 4.
Total heat-related economic costs in an Italian farm based on the productivity loss calculated based on the epidemiological function during summers 2017 and 2018. Different letters indicate statistically significant differences ($p < 0.05$) between working times.

7% and 6% in Guangzhou (little more than 60% reduction compared to working in the sun) and it was lower than 0.5% in Florence (little more than 80% reduction compared to working in the sun).

4. Discussion

This study is a concrete example of how even simple precautions, e.g. work in the shade or work-time shifting, represent effective adaptation strategies to reduce the typical PL of outdoor agricultural workers due to the increasing heat stress and consequently the economic cost during the summer season. The main findings of this study can be summarized as follows:

1. The hourly PL and the related economic cost of agricultural workers decreased significantly by working in shady conditions and by work-time shifting, showing improvement effects especially by anticipating the typical working time by 2 h (start working at 6 a.m.).
2. Hourly PL values estimated in all working times by using the Florence airport meteorological data were lower than that estimated by using the local farm meteorological data.

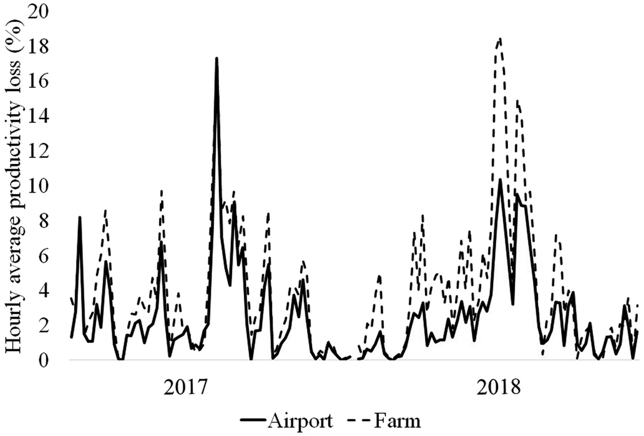

Figure 5. Hourly productivity loss in the sun estimated during the typical working time ($WT_{8\text{-}17}$) by using the epidemiological function based on meteorological data recorded in Italy (Tuscany) at the city-airport (continuous line) and the rural-farm (dashed line) during summers 2017 and 2018.

Table 2. Hourly productivity loss (%) calculated with the epidemiological function for workers exposed to the sun and working in shady areas in Florence (Italy) and Guangzhou (China) during the summers of 2017 and 2018

Working times	Productivity loss (%) for workers exposed to the sun [mean WBGT ± SD]		Productivity loss (%) for workers in shady areas [mean WBGT ± SD]	
	Florence	Guangzhou	Florence	Guangzhou
$WT_{8–17}$	2.4% (2.2–2.6) [24.2 °C ± 3.1]	17.4% (16.8–18.0) [29.5 °C ± 2.1]	0.4% (0.4–0.4) [21.8 °C ± 2.4]	6.8% (6.6–7.0) [27.5 °C ± 1.4]
$WT_{7–16}$	2.1% (1.9–2.3) [23.4 °C ± 3.6]	17.0% (16.4–17.7) [29.4 °C ±2.1]	0.3% (0.3–0.4) [21.3 °C ±2.7]	6.4% (6.2–6.6) [27.4 °C ± 1.4]
$WT_{6–15}$	1.9% (1.7–2.1) [22.4 °C ± 4.3]	15.8% (15.1–16.5) [29.0 °C ± 2.4]	0.3% (0.2–0.3) [20.6 °C ± 3]	5.9% (5.7–6.1) [27.2 °C ± 1.5]
p-value	<0.001	<0.001	<0.001	<0.001

Note(s): Confidence intervals are indicated in round brackets. Hourly mean WBGT ± the standard deviation are indicated in square brackets

(3) Significantly higher PL values were observed in the Chinese subtropical area than that estimated in Florence.

(4) The decrease of PL observed by work-time shifting (anticipating the typical working time) was greater in Florence than in Guangzhou.

The fundamental assumption of this work is based on the fact that when heat stress conditions occur, workers adapt their behaviour by taking longer and more frequent breaks (for resting and drinking); they generally slow down their work activities with the aim to maintain the core body temperature in safe limits. This assumption is even more robust increasing the intensity and the duration of the physical activity, consequently rising the metabolic heat production inside the body with higher risk of heat-related illness. This situation translates into a reduction of the effective working time causing a general PL and a consequent economic cost.

Studies that have tried to quantify the heat effect on workers' productivity and to estimate the economic impact are still very few (Roson and Van der Mensbrugghe, 2012; Chinnadurai *et al.*, 2016; Kjellstrom, 2016; Takakura *et al.*, 2017; Budhathoki and Zander, 2019; Vanos *et al.*, 2019). However, the exposure to heat stress is expected to increase significantly in the next years because of climate change (Mora *et al.*, 2017) also in areas where the worker population is not used to fighting this phenomenon (Kjellstrom *et al.*, 2018). In addition, as described in a recent report of the International Labour Organization (Kjellstrom *et al.*, 2019b), the cost to the world economy due to decreased labour productivity (especially due to the incessant increase in heat) is expected to be greater than that caused by any other major disruption related to climate change. For this reason, effective adaptation measures to the heat stress and the implementation of control measures in the workplaces are urgently needed to protect worker's health and economic losses (Chinnadurai *et al.*, 2016; Takakura *et al.*, 2017; Meegahapola and Prabodanie, 2018; Day *et al.*, 2019). Taking breaks in shady or cooled areas during working time according to specific heat stress conditions and physical efforts represent a fundamental heat-related adaptation method recommended by the International Organization for Standardization (ISO-7243, 2017) and other governmental agencies (ACGIH, 2015; NIOSH, 2016).

A recent study (Takakura *et al.*, 2017) provided a comprehensive assessment of the economic cost of heat-related illness prevention through worker breaks in the workplace. In particular, the authors calculated the heat-related worker breaks depending on the WBGT and the intensity of physical activity as reported in international standards (NIOSH, 2016; ISO-7243, 2017); however, our study revealed that the heat-related PL for moderate work activity could be more limited if a risk function based on epidemiological data is applied. This aspect is of great importance because the most accurate estimation of the heat-related PL should be based on epidemiological evidences.

However, because of the great difficulty in collecting quantitative information on PL directly in field work situations, only a few studies are available and the most detailed was carried out by Sahu *et al.* (2013) who estimated that approximately 5% of the work output at 26 °C in the first hour was lost for each °C of WBGT increase. This is one of the main limitations of our study where calculations are applied uniformly over the entire study population without considering any physical and or physiological variations, age factors and any morbidities that might play a significant role in work capacity of the workers. It is also necessary to consider that the overall costs estimation of the heat-related PL of workers involved in the wine sector for the whole province of Florence was calculated accounting for the AWU method who considers a full-time job. However, in the agricultural sector, and also in the wine sector, most are seasonal workers and for this reason, their number may change during the year. In addition, the qualitative aspect, which certainly represents another useful information for a more accurate estimate of the heat-stress-related cost, has not been analysed. The working quality depends, for example, by the timing when different work mansions are carried out, the use of personal protective equipment and work tools to carry out certain tasks, or worker's acclimatization. It is known that the heat stress has direct effects on the physical performance (mainly because of dehydration) as well as on cognitive functions (Cheung *et al.*, 2016; Piil *et al.*, 2018), therefore reducing the quality of the work done and increasing the risk of accidents in the workplace. For these reasons, future studies on PL and cost estimations should also focus on the qualitative aspect. The latter will also be one of the goals of an Italian project of the National Institute for Insurance against Accidents at Work, whose acronym is "WORKLIMATE", that is about to start and that will focus on the social cost of accidents at work and on heat-related adaptation strategies for workers also accounting for qualitative information.

However, based on the currently available data, this study provides a good and useful example of quantitative estimate of the potential hourly PL of workers involved in moderate work activities in sun and shady areas in relation to thermal stress and that can be validated when field data will be available.

The work of Takakura *et al.* (2017) suggested that shifting working time is also an effective adaptation measure to reduce the economic cost of heat-related illness prevention through worker breaks, and the authors concluded that future studies should quantitatively investigate the effectiveness of these adaptation measures in relation to outdoor work. A subsequent interesting study carried out by the same authors (Takakura *et al.*, 2018) also quantified on a global scale (grid cell of 0.5° x 0.5° resolution) the working time shift in hours that will be required in the future (based on climatic scenarios) to offset the labour capacity reduction. The authors partially confirmed the effectiveness of shifting working time also stating that climate change mitigation actions remain indispensable to counteract the increasing heat. However, this last study still had the limitation that it does not consider the hourly labour capacity calculation based on a more realistic epidemiological function (Kjellstrom *et al.*, 2018). In addition, for the purposes of the work itself, these studies (Takakura *et al.*, 2017, 2018) calculated the labour capacity for grid cell at low resolution (about 50 km resolution) and therefore useful for having a global picture but less representative of the real local situation. In fact, in this type of studies, some bias in the estimation of the WBGT could occur. Our study responds precisely to this last requirement providing accurate microclimatic monitoring at a local farm scale with the aim to obtain detailed and reliable quantitative information on the effectiveness of a specific heat-related adaptation strategy (the work-time shifting) useful for limiting the heat-related PL and the consequent economic cost. The present study also revealed the importance to estimate PL on the basis of local microclimate data: important PL differences can also be observed using microclimatic data recorded in areas not far from each other but located in different environmental contexts (i.e. peri-urban or rural areas). Our findings even revealed that the estimated PL during working hours was higher in a rural area (farm), characterized by high humidity rates and less ventilation, compared to a peri-urban area (where the airport is located), although the latter had shown an average air temperature higher than the rural area. Studies in outdoor environments, where especially the solar radiation might play a strong contribution in determining heat stress for outdoor workers, great attention should be addressed to the measure of T_g. In general, the outdoor monitoring of this parameter is carried out for study purposes and very limited time periods (some hours of monitoring). In our study, T_g was monitored outdoors at the farm every hour continuously for two summers (2017–2018). This represents a strength point because it allows the availability of a relatively long time series of T_g values directly measured in work field (also potentially useful for validation of T_g values estimated from global low-resolution models) and not its estimation obtained through modelling approaches by using other variables and which can favour bias in the WBGT calculation. In this way, the accurate estimation at the farm of the outdoor heat-related PL during different daily working times revealed significant PL reductions by shifting the working time (starting earlier in the morning) and working in shady areas. In particular, the "typical" heat-related PL in the sun and the consequent economic cost calculated over the entire study period could have been reduced up to 33% by starting to work 2 h before (starting at 6 a.m.) the typical working time. This result support the conceptual framework provided by Day *et al.* (2019) useful to help decision makers identify suitable climate-related adaptation options to counteract the effects of heat. These authors stated that behavioural measures such as changing working hours to avoid the hottest parts of the day, together with regular drink breaks, might be effective and often cheaper than technical solutions in dealing with temperature peaks especially for outdoor workers. However, our findings also revealed that this behavioural solution reduces the problem of the heat-related PL but does not allow a complete resolution of this phenomenon because an hourly PL in the sun ranging from 2.7% to 3.8% (depending on the PL function adopted) during the summer period is shown even starting to work early in the morning. This result is in agreement with the recent work of Takakura *et al.* (2018) that confirmed the effectiveness of shifting working time (starting earlier in the morning) as an adaptation measure for reducing, but not completely eliminate, the problem of the labour capacity reduction due to climate change. For this reason, they highlighted the importance of climate-change mitigation to minimize the impact of heat. In particular, the authors stated that outdoor workers in many parts of the globe should start working before sunrise if they want to substantially contain the labour capacity reduction. However, shift work alters the usual living patterns of the worker and result in some degree of sleep deprivation whose effects in living patterns on heat tolerance are mostly undocumented (NIOSH, 2016), and for this reason, the shift of working time should be reasonably contained. In addition, it must also be considered that changing working time may be constrained by cultural factors (Day *et al.*, 2019). Nevertheless, in Tuscany, many farms usually change their working time during the summer generally starting the early morning hours and in any case by interrupting the intense work activities during the early afternoon. At Italian latitude, starting to work at 6 a.m. means starting after sunrise during June and July but also start working before sunrise during August and above all September.

However, our study has also shown that another adaptation measure, such as favouring work in shady areas, can significantly improve the situation, bringing the hourly PL for the Italian location on very low values, largely below 1%. Therefore, improving the effectiveness of the rest periods by making the workers rest in shady and well-ventilated areas or still using mobile shading structures (even simply large umbrellas or gazebos with wheels) represent solutions that could significantly reduce the heat-related PL and the consequent economic impact preserving the worker's health. In addition to the preventive measures previously described, other strategies can also be adopted with the aim to protect worker's health and to reduce PL. Together with governments, both employers and workers should be involved in the design and implementation of the best mitigation and adaptation policies (i.e. reorganization of production processes, how to adjust working hours, how to distribute the various work activities throughout the day, technological improvements, etc.), in this way ensuring compliance with health and safety standards and finding practical solutions to enable workers to cope with high temperatures and allowing employers avoiding or limiting PL (Kjellstrom, 2019b). A recent technical report developed in the framework of the HEAT-SHIELD project (Technical Report 12 - D4.1 Final Report (WP4) available at: https://www.heat-shield.eu/technical-reports) described and updated, based on the recent scientific knowledges, the various solutions and strategies to mitigate or minimize negative effects of excessive heat exposure in the agricultural sector. In particular, it is advisable that agricultural firms (independently from the firm size) consider/develop an appropriate heat response plan useful for both employers and employees. The report describes in detail the hydration options, characteristic of breaks, timing of work, cooling interventions during breaks and works and clothing strategies that should be brought to the attention of agricultural workers through their employers with the aim of protecting the worker from the dangers of the heat and preserving productivity. More field studies are needed to investigate the role of these and other factors in PL reduction, also supporting our results. A useful adaptation strategy is the recently developed multilingual European "HEAT-SHIELD occupational warning system" platform (https://heatshield.zonalab.it/). This forecast system contains customized information for workers (based on the physical demands of the job as well as on workers' physical, clothing and behavioural characteristics and on the work environment), includes short-term (5-day forecasts) recommendations related to how much hydrate (water intake) and rest (work breaks) useful to help heat adaptation for workers and also provides long-term heat-risk forecasts (up to about one month) for planning/organizing work activities useful for employers, organizations and operators in charge of safeguarding health and productivity in various occupational areas (Morabito *et al.*, 2019). Because of the increasingly evident effects of climate change that find the highest expression in global warming, more and more attention will have to be addressed to implement effective heat-related adaptation strategies to reduce (or at least to contain) the expected PL in many occupational sectors. As reported by a recent work (Kjellstrom *et al.*, 2018), the severe heat stress conditions and the consequent substantial reduction of work capacity and labour productivity that are currently affecting for long time-periods some tropical and subtropical areas, will soon affect wide areas of the world, including southern parts of Europe. The comparisons between PL values estimated in Chinese subtropical and Italian Mediterranean cities shown in our study revealed how important is this investigation in various geographical areas of the planet that may require suitably different strategies to counteract the effects of heat in the workplace based on local microclimatic characteristics. For example, our study has shown that in Guangzhou, it is much better to prefer work in the shade than to anticipate working time because thermal stress remains unchanged even anticipating work-time: the average values of WBGT always remain close to 29 °C. In addition, in-depth knowledge of the effect of heat stress on PL in other geographical areas that are already experiencing detrimental heat stress conditions (taking into consideration the substantial differences in terms of sunrise/sunset time, the solar angle and the diurnal WBGT variation) might help to plan heat-related occupational prevention strategies in other areas, such as Mediterranean cities, to counteract the increasing heat stress forecasted in the next years due to global warming. The Mediterranean area, together with other European areas, is considered one of the most prominent "Hot-Spots" in future climate change projections (Giorgi and Lionello, 2008), also confirmed by the Fifth Assessment Report of the IPCC (IPCC, 2014). Based on the Climate Chip Web platform, thermal stress conditions predicted in Florence for the period 2071–2099 will be in several months similar to those currently observed in Guangzhou (period 2011–2014) (Figure 6). In particular, Florence will experience maximum monthly WBGT values higher than 28 °C in July and August by the end of this century with significant impacts on hourly PL as Guangzhou is already experiencing.

Consequently, Italy would also experience severe losses in agricultural production, due to physical factors, such as the increased temperature and reduced water availability (Galeotti and Roson, 2012), but also due to factors related to the health of agricultural workers who, exposed to conditions of heat stress for increasingly persistent periods, will see their productive efficiency at work significantly reduced. This aspect is of great importance in the wine sector of Tuscany: wine cultivation represents one of the pillars of agriculture in this region, with important effects on the local economy. Unfortunately, the share of agriculture of the total GDP decreased in Italy since 2000 (it was 2.6% of GDP) reaching 1.9% in 2017 (https://data.worldbank.org/indicator/NV.AGR.TOTL.ZS?locations=IT&view=chart).

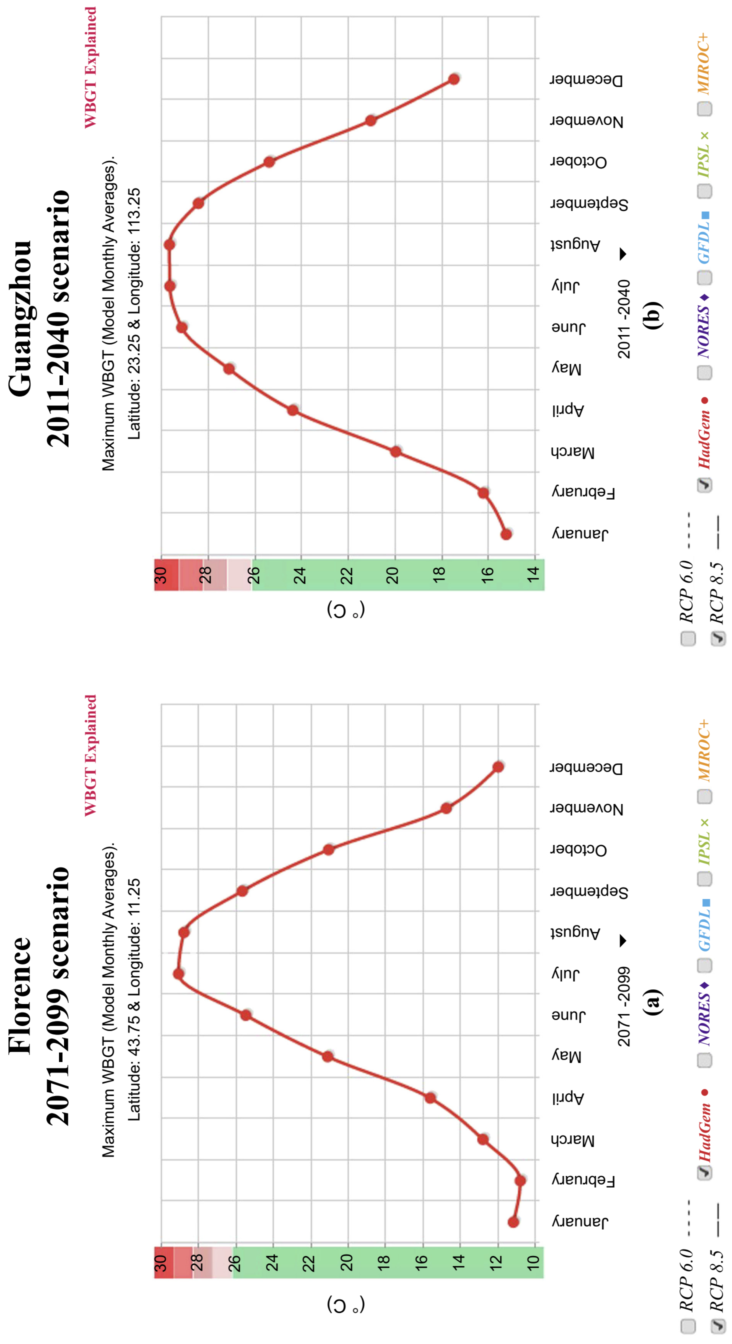

Figure 6. Maximum monthly WBGT predicted based on the UK Met Office model HadGEM2-es (HadGem) and RCP 8.5 for the period 2071-2099 in Florence (a) and for the period 2011-2040 in Guangzhou (b) (source ClimateCHIP website: http://www.climatechip.org/).

Considering only the situation in central Italy (the area where the farm involved in our study was located), the estimate of the GDP in the agricultural sector referring to 2017 has shown a marked decline compared to 2016 (−8.4%) (https://www.istat.it/it/archivio/217603). This reduction (especially observed in the wine sector) is certainly due to the adverse weather conditions that characterized much of 2017 (e.g. the dry summer). In particular, the summer of 2017 was yet another summer with temperatures decidedly above average in the province of Florence and with widespread heat stress conditions for workers. The 2017 was one of the harvests most affected by the climate change of the last few years, both in terms of quality and quantity, with a strong reduction in wine production in Tuscany: 1 million hectolitres less than the previous year (1 million 600 thousand hectolitres), with a decrease of 38% based on the Tuscany Region report relating wines in Tuscany in 2017 (https://www.toscana-notizie.it/-/scheda-il-rapporto-sui-vini-in-toscana-nel-2017).

As the effect of heat stress on labour productivity is considered a key economic impact of climate change, which could affect national output and workers' income (Day *et al.*, 2019), a better management of the agricultural workforce through behavioural measures (i.e. work-time shifting) during the summer period would certainly represent a strong point to limit the economic cost. These adaptation strategies, together with mitigation actions, are strongly recommended and urgently needed especially for outdoor workers committed to work in increasingly intense and persistent heat stress conditions which will affect wide geographical areas in the coming years.

5. Conclusions

This study confirms the hypothesis that the typical expected heat-related PL of outdoor agricultural workers engaged in a moderate activity (300 W) might be reduced during the hottest season by easy adaptation actions, such as working in shady conditions and by the work-time shifting. However, these strategies are improvement but not decisive actions to reduce the heat effect. In fact, PL still occurs even anticipating the working time of a couple of hours (starting to work early in the morning, around sunrise), although with significantly lower PL values than that estimated during the typical working time (from 8 a.m. to 5 p.m.).

The choice of the risk function to be used for estimating the heat-related PL, and the consequent economic cost, significantly influences the results: PL can be more limited if a risk function based on epidemiological data rather than the ISO-standard is used. Future studies will also have to consider the estimation of PL for workers engaged in activities with different intensity of effort.

Studies related to field monitoring and allowing the collection of detailed data aimed at quantifying the beneficial effects due to the implementation of specific adaptation measures for limiting the heat-related PL and the consequent economic cost are urgently need. In addition, the study of heat-related PL in various geographical areas of the planet and above all those that are already experiencing severe and persistent heat stress conditions can provide important indications to put into practice the best policy intervention and forward planning to counter the impending effects of climate change in Mediterranean areas.

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