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Economic impact of labor productivity losses induced by heat stress: an agent-based macroeconomic approach

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Abstract

Against the backdrop of rising temperatures, this paper analyzes how prolonged heat affects labor productivity and the corresponding macroeconomic outcomes, using Austria as a case study. While previous research primarily focused on specific industries or used industry aggregates, this study also considers inter-industrial economic connections. We assess the macroeconomic effects of an increase in seasonal heat stress triggered by climate change with an emphasis on (1) industry-specific work intensity and (2) the vulnerability to heat-induced impairments resulting in an industry-specific loss of labor productivity. To account for indirect and non-linear economic relationships, we apply an agent-based model of the Austrian economy, which translates heat-induced productivity losses into economy-wide effects via shocks to industry-related input-output structures on the level of economic agents. The findings highlight how in the scenario with the highest temperature increase, the largest average loss in real GDP amounts to 0.7% in the third year compared to the baseline scenario. The largest aggregate effect is found for investments in dwellings. In line with existing literature, industries most affected directly are those that perform intense work in the sun, such as agriculture and construction. Our methodological approach, model, and the corresponding EU data sources can serve as a blueprint for further comparative research.

Keywords Agent-based model · Work intensity · Labor productivity · Climate change · Heat stress · Industry-disaggregated

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1 Introduction

Europe's future climate, in line with a grave worldwide situation as outlined by the Sixth Assessment Report of the International Panel of Climate Change (IPCC 2023), paints a highly concerning picture. Rising temperatures are expected to become the global norm and are currently observed worldwide with astounding speed. Given the limited ambition of committed nationally determined contributions (NDCs) to mitigate climatic change, IPCC projections suggest that it will be very difficult to stabilize global temperature increase below 2.0 °C by the end of the 21st century (IPCC 2023). Average temperature increases also translate to a significant rise in the number and extent of heatwaves during summertime - with scorching days and sleepless nights becoming more frequent and intense. The increase in frequency, intensity, and duration of heatwaves is projected to be especially pronounced in the Mediterranean region (Lorenzo et al. 2021; Molina et al. 2020).

The World Health Organization (2024) highlights the dangers these heatwaves may pose to human health, particularly for vulnerable populations. Heatstroke, dehydration, and worsened pre-existing health conditions could become a grim reality for many. These extreme temperatures will negatively impact health and strain infrastructure and emergency services, potentially leading to cascading effects on economic output and structures, population health, and human well-being. Thus, a methodology is needed for evaluating the influence of prolonged extreme temperatures on human activities in the economy, for a specific national or geographic scope. With such a specific approach, an individual study can serve as a blueprint of how this methodology can be applied to different regions in Europe, which are all affected very differently by global climatic changes.

Induced by the expectations of such dramatic temperature increases, the impact of heat stress on labor productivity has emerged as a critical concern in recent years. Heat stress, characterized by excessive heat exposure exceeding the body's capacity for thermoregulation, poses significant challenges to workers across different occupational settings. As temperatures rise globally, better understanding the complex impact of heat exposure on the human body is essential for informing policy interventions and workplace practices, aiming on the one hand at safeguarding workers' health and well-being, and on the other hand at keeping up labor productivity and, more generally, economic output. The International Labor Organization (ILO) (2019) projects a worldwide reduction of overall working hours by 2.3% in 2030. The loss of work capacity due to heat varies greatly depending on the region (e.g., García-León et al. 2021). Kjellstrom et al. (2016) estimate a current loss of labor productivity during daylight hours in especially hot areas of 10%, which is projected to rise locally to 30 or 40% by 2085. Szewczyk et al. (2021) calculate an aggregate European labor productivity loss of 1.6% in the 2080s, but over 8% in several regions in Southern European countries. According to the ILO, more than 2.4 billion workers (out of a global workforce of 3.4 billion) are likely to be exposed to excessive heat at some point during their work. In relation to the global workforce, the proportion has increased from 65.5% in 2000 to 70.9% in 2020 (International Labour Organization 2024).

While there are multiple impacts of heat on society and the economy, this paper seeks to explore the effect of prolonged heat stress on a macroeconomic level, with specific emphasis on (1) the effect's relation to work intensities characterized as industry-specific levels of light, moderate and heavy work, and (2) on the vulnerability to heat-induced impairments resulting in an industry-specific loss of labor productivity. We applied an agent-based model (ABM) to evaluate the potential economic effects of recurring seasonal heat stress on labor productivity, which translates industry-level productivity losses into economy-wide effects via shocks to industry-related input-output structures on the level of individual economic agents. This approach allows the combination of macroeconomic perspectives, environmental-scientific climate data, and insights from health economics.

Given the estimates of temperature increases for Austria, we found significant but economically manageable effects of heat stress-induced productivity losses on output, employment, and other main macroeconomic aggregates. Building on these first insights, our methodology could serve as a blueprint for further studies on the economic effects of heat stress for different countries in Europe. For other regions with more dramatic heat stress conditions than Austria, such as in Southern Europe, these effects could become more pronounced and deliver important insights for climate adaptation.

The structure of the paper is as follows. The second section outlines the theoretical background by providing a review of the literature on heat stress and labor productivity. Section three describes the data used and introduces the ABM applied for the simulations. The fourth section presents the results of these calculations, leading to a comparison with existing empirical results and a discussion of the limitations.

2 Economic analysis of heat stress

2.1 The connection between heat stress and labor productivity

The human body stabilizes its core temperature at a constant thermal level that provides an optimum for its metabolic processes to function. For that, heat exchange is necessary and occurs via the process of sensible heat transfer (conduction, convection, and radiation) when temperature differences with the surrounding environment exist, as well as through evaporation of sweat when such differences do not exist (Parsons 2014). Six factors mainly determine the possibilities of thermoregulation: Air temperature; radiant temperature; humidity; air velocity; metabolic heat, generated by human activity; and clothing worn by a person (Parsons 2014, p.2). The most common index to assess heat stress is the *Wet Bulb Globe Temperature* (WBGT) which has been utilized for several decades. Besides (air) temperature, the WBGT also includes humidity, wind speed, the angle of the sun as well as cloud cover as a proxy for solar radiation and can be calculated for indoor and outdoor conditions (e.g., Kjellstrom et al. 2009; for calculation see Parsons 2006). It is measured by “weighting (…) dry-bulb temperature, natural (un-aspirated) wet-bulb temperature and black-globe temperature” (Blazejczyk et al. 2012, p. 518). At high WBGT°C values, many of these determining factors are non-favorable for a dry heat transfer from the body to the environment thus, evaporation of sweat becomes necessary to balance metabolic heat (Parsons 2014).

Besides the WBGT there are plenty of other indices aimed at rating thermal (dis)comfort. Epstein and Moran (2006), for instance, list 45 different systems for assessing heat stress from the beginning of the 20th century onwards. Few of these indices have prevailed, among them the *corrected effective temperature* (CET), the *discomfort index* (DI), and the WBGT (Rachid and Qureshi 2023). A more recently developed relevant metric is the *Universal Thermal Climate Index* (UTCI), which measures heat stress by taking into account temperature, wind, humidity, and average radiation temperature (Blazejczyk et al. 2012). We use the WBGT, as it remains the most widely applied heat stress index in the respective labor productivity literature and is linked to international labor standards (Kjellstrom et al. 2009; International Organisation for Standardisation 2017).

ISO 7243 offers a comprehensive framework for assessing heat stress in occupational settings, considering factors such as environmental thermal conditions, intrinsic heat generated through physical activity, and the influence of work attire (International Organisation for Standardisation 2017). The systematic approach provided by this international standard allows for a thorough evaluation of heat exposure among workers. To mitigate health effects arising from heat stress among workers, ISO 7243 further provides guidelines delineating a reduction in hourly work output across varying work intensities. This involves a standardized classification of work intensities corresponding to metabolic rates. These metabolic rates serve as proxies for estimating the internal energy expenditure associated with different work intensities (International Organisation for Standardisation 2017). Kjellstrom et al. (2009) take the ISO standard and expand on it. In their paper (2009, 3–4), they differentiate between five metabolic rate classes:

1) 0 (rest): M = 100 Watts, WBGT = 33 °C.
2) 1 (light work): M = 200 Watts, WBGT = 30 °C.
3) 2 (medium work): M = 300 Watts, WBGT = 28 °C.
4) 3 (intense work): M = 400 Watts, WBGT = 25 °C.
5) 4 (very intense work): M = 500 Watts, WBGT = 23 °C.

The approximate metabolic rate M describes an intensity of physical activity at work. The corresponding WBGT values serve as reference values at what WBGT the direct heat stress should be reduced. According to ISO 7243, these guidance values should not be exceeded to not risk overheating when working at the given work intensity. Apart from ISO 7243 there are several exposure-response functions in the literature that address a decrease in labor productivity due to heat, most of which use experiments for modeling (Dasgupta et al. 2021). Kjellstrom et al. (2009) also associate these values with needed rest times. Similar to other papers (e.g., Szewczyk et al. 2021), we differentiate between light (1, 200 W), moderate (2, 300 W), and heavy (3, 400 W) work. In addition to these estimations, the differentiation between indoor and outdoor work is added to integrate the effects of thermal comfort in line with ISO 7243 and Kjellstrom et al. (2009).

Therefore, the effects of heat stress on labor productivity depend on the workplace conditions based on the type of work and the respective activity level. The biggest impact is expected to be found in industries with a lot of physically demanding work, particularly work that tends to be done outdoors. Some of the relevant literature focuses only on specific industries, such as agriculture (Pogacar and Črepinšek 2017), manufacturing (Somanathan et al. 2021), or mining (Nassiri et al. 2017). Other research takes the economy as a whole into account, but only uses a highly aggregate distinction, for instance between low-exposure industries that tend to be indoors or in the shade and high-exposure industries with a lot of outdoor work (Dasgupta et al. 2021).

In their meta-analysis, Flouris et al. (2018) defined hot working conditions for heavy labor jobs as >22 WBGT°C (>25 WBGT°C for most other jobs). They examined literature indicating that people working in hot conditions were four times more likely to suffer from heat-related stress during or at the end of their work shift, compared to those working in a comfortable environment. The core body temperature of people who worked one shift under hot conditions was on average 0.7 °C higher and in the long run, 15% of those who regularly worked under heat conditions (i.e., every day for 2 months of the year) suffer from kidney problems. However, heat exhaustion as well as other effects such as cardiovascular problems and even cardiac arrest may already occur after being exposed for a short period of time (Kjellstrom et al. 2016).

The effects of heat on the human body can be mitigated by several factors. Automatic responses from the body include processes of acclimatization that lead to an improved heart rate when exposed to heat (Périard et al. 2021), quicker and higher sweat rates as well as a lower salinity in sweat, which improves the electrolyte balance (Parsons 2014). Additionally, from a psychological perspective, the expectation of and preparation for upcoming heat can improve individual satisfaction with the respective thermal environment (Parsons 2014) and thereby influence mental capability to be productive.

Besides the abovementioned autonomous heat regulation, behavioral responses such as taking off clothes, taking more breaks, drinking more, and seeking shade are further natural human adjustments for thermoregulation. This can also be seen as a mechanism to regulate the pace at which working tasks are performed (Périard et al. 2021). With regards to productivity, it is important to acknowledge that decreases during heat exposure may happen because of slower and less precise performance during the actual working time as well as through de facto less available working time because of behavioral responses like additional (drinking) breaks. (Dasgupta et al. 2021; Kjellstrom et al. 2016). Apart from the stated individual adjustments, the International Labour Organization suggests further measures to protect workers from heat on the level of governments and employers. Among others, these measures include the provision of air conditioning and ventilation indoors, regulations like guaranteed access to water and shade, heat sensible clothing as well as enablement of flexible working times to escape from heat (International Labour Organization 2019). Within existing literature, these have been shown to not only benefit workers health, but also support the maintenance of productivity levels during heatwaves (Morabito et al. 2020; Park 2017; Zivin and Khan 2016).

This paper investigates the effect of prolonged heat on the macroeconomic level, focusing specifically on the relation between various industries and their susceptibility to heat-induced labor productivity losses. The framework given by ISO 7243 and the mentioned classification of different work intensities were taken as a guideline to evaluate and estimate work intensities throughout different industries.

2.2 The economic effects of heat stress

Zhao et al. (2021) conducted a systematic review of the methodologies used to evaluate the economic losses caused by a decline in labor productivity associated with heat stress. They differentiate between studies that investigate the direct impacts (Human Capital (HC) and Econometric method) as a loss in production output or income loss and studies that consider indirect impacts (Input-Output method and computable general equilibrium (CGE) modeling) through interdependencies across industries. According to Zhao et al. (2021), only a few studies consider comprehensive direct and indirect economic impacts. The approach chosen for this paper resembles the HC method. In this method, the economic impact corresponds to the lost income or production output. Also, the production functions are chosen to not allow for a substitution of production factors (Zhao et al. 2021), as further described in Sect. 3.

Szewczyk et al. (2021) calculate economic losses with published exposure-response functions to four occupational groups and integrate these productivity losses under the collected WBGT projections of 11 climate models into a country-specific dynamic Solow growth model with 30-year average losses until 2080. This differs substantially from our modelling approach and the industry-disaggregated methodology which is further explained in Sect. 3. For Europe, they calculate economic losses up to 63 billion Euro or 1.15% of GDP in the worst-case scenario until 2080 with a highly uneven distribution across Europe (Szewczyk et al. 2021). Central European countries are expected to lose 0.6% of GDP in the mean and 1.1% in the worst-case scenario by 2080. Southern European countries could lose up to 3–5% of GDP only through labor productivity losses by 2080 under worst-case scenarios. The calculated losses by Szewczyk et al. (2021) underline the necessity of a comprehensive and cross-industrial dependency evaluating approach.

For Austria, the COIN project (Urban and Steininger 2015; Steininger et al. 2016) analyzed the labor productivity losses of “manufacturing and trade”, using the relationship between the WBGT and the productivity of workers. For their analysis, the authors used the HC method and GDP/employee for quantifying direct productivity losses and fed the outcome as input into a CGE model to assess the macroeconomic implications. The future climate and socioeconomic scenario used as projections for WBGT and input for the CGE model by Steininger et al. (2016) is in line with the “Shared Socioeconomic Pathway 2” which refers to “intermediate challenges” for adaptation and mitigation measurements. This is also reflected in the exogenous inputs regarding economic growth, demographic change, land use, and technological development used for the CGE model as a reference scenario for the considered period (Steininger et al. 2016). They find that the direct impacts increase three- to fourfold when considering macroeconomic feedback effects. The decline in economic welfare amounts to 6 million Euro per year in their mid-range climate scenario for the period 2016–2045 (54 million Euro for 2036–2065), in the high-range scenario they estimate a loss of 58 million Euro (296 million Euro). GDP losses are 1.5 times larger given the price declines triggered by declining demand. However, the authors only considered productivity losses in “manufacturing and trade” and found that this impact is small compared to the climate change-related macroeconomic effects of catastrophe management, agriculture, forestry, electricity, supply, tourism, and temperature regulation (Steininger et al. 2016). The scenario used for this paper follows the SSP3-7.0 which is described in more detail in Sect. 3.2. This includes different expectations on future climate and socioeconomic projections and therefore predicted increase in heat which serves as an explanation for the deviating results which is further explained in Sect. 5 (Intergovernmental Panel on Climate Change (IPCC) 2023).

3 Methods and data

3.1 The macroeconomic agent-based model

The ABM used for this analysis is described in detail in Poledna et al. (2023). We contend that an ABM is the best choice to account for the complex economic dynamics resulting from productivity shocks. Alternatives such as CGE and Dynamic Stochastic General Equilibrium models focus on modelling individual agents' behavior based on optimization and rational expectations, while mostly abstracting from networked connections (Haldane and Turrell 2018). Equilibrium models generally struggle with incorporating non-linearity, irreversibility, and tipping points. ABMs can endogenously exacerbate crises, fluctuations and volatile growth, contrary to most general equilibrium models that display smooth economic growth paths unless shocked exogenously (Balint et al. 2017). Given the strong sectoral variations of the heat-stress induced labor productivity shocks, as well as due to the expectations of non-linear and knock-on effects, our analysis with an ABM adds valuable insights to this pressing economic question.

Here, we only provide an overview of the main characteristics of the ABM we use. The model economy is structured into five sectors (non-financial companies, private households, the government, the financial sector including the central bank, and the rest of the world) as defined by the European System of Accounts (ESA) (Eurostat 2013). Figure 1 in the supplementary material provides a graphical representation of the structure of the model.

3.1.1 Agents and sectors

(1) The firm sector (*non-financial corporations*) comprises 64 industries (NACE/CPA[1] classification), each producing a perfectly substitutable good. Each firm is part of one industry and produces an industry-specific output with an industry-specific, fixed-coefficients Leontief technology (Leontief 1951) production function with labor, capital, and intermediate inputs from other industries. The number of firms in each industry is derived from business demography data, while firm sizes follow a power law distribution. All agents in the model are subject to uncertainty and form expectations about output and inflation. Given these assumptions, they estimate future demand for their products, input costs, and the profit margin. According to these expectations– which are not necessarily realized– firms set prices and quantities. Expectations are formed using simple AR (1) rules.[2] On markets characterized by search and matching, output is sold to households and to other firms, to the government, or to the rest of the world. Investment is based on the expected wear and tear on capital. Firms are owned by investors, who receive dividend income.

(2) *Private households* earn income, consume, and invest in dwellings. Again, the market structure is characterized by search and matching. Households may be employed, unemployed, investors, or inactive. Employed households supply labor and earn sector-specific wages. Unemployed households receive unemployment benefits.

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[1] Classification of product by activity.

[2] In an autoregressive model of order one [AR (1)], a variable is assumed to depend on its own realization in the previous period and on a stochastic error term.

Investor households obtain dividends from firm ownership. Inactive households do not participate in the labor market and receive social benefits. Additional social transfers are distributed equally to all households (e.g., childcare benefits). Like firms, households form expectations using AR (1) models.

(3) *The government* purchases goods and services and redistributes income in the form of social benefits. Government revenues consist of taxes, social security contributions and other transfers. Government expenditures are composed of government consumption, interest payments on government debt, social benefits, subsidies and other expenditures.

(4) *Financial corporations* obtain deposits from households and firms and provide loans. Interest rates are set by a markup on the policy rate offset by the European Central Bank (ECB). Credit creation is limited by minimum capital requirements, and loan extension is conditional on a maximum leverage of the firm. Bank profits are defined as the difference between interest payments received and deposit interest paid, as well as write-offs due to credit defaults. *The central bank (i.e., the ECB for Austria as part of the euro area)* sets the policy rate according to a Taylor rule based on inflation and growth targets. While the ECB primarily focuses on achieving the inflation target of 2%, in its actual policy it also takes other factors affecting inflation such as the output gap into account. In addition, the central bank provides liquidity to the banking system and takes deposits from the banks in the form of reserves. Furthermore, the central bank purchases external assets on the open market.

(5) Interactions with *the rest of the world* take place as exports and imports of goods and services. By modelling a small open economy, whose decisions do not affect world prices, we treat exports and imports as exogenous.

3.1.2 Market structure

Interactions between the agents take place on decentralized markets characterized by search and matching: Sellers are matched with buyers using randomized algorithms that allow for friction. This enables ABMs to capture institutional settings of specific markets and to represent shortages of supply or demand and the occurrence of frictions on markets (Dawid and Delli Gatti 2018). The decentralized search and matching mechanism rests on the probability of a firm to be visited by a certain agent to purchase a product. This probability depends (1) on the price, and (2) on the size of the firm, i.e., larger firms have a higher probability of being visited.

In the aggregate, goods markets in the ABM are efficient in the sense that there is no "frictional" excess demand or supply. However, if aggregate demand exceeds aggregate supply, individual consumption budgets may not be exhausted. The opposite case can also be relevant, i.e., that (some) firms cannot sell all their output. In the absence of large endogenous fluctuations or exogenous shocks, the ABM tends towards an approximate equilibrium state, and markets tend to be close to the equilibrium state where demand and supply match.

3.1.3 Modifications for the analysis of productivity losses induced by heat stress

For the present paper, the ABM, as described in Poledna et al. (2023), has been modified regarding three aspects. Firstly, heat-induced productivity losses are incorporated in the production function. Secondly, stocks of capital and input goods are held at firm-specific target levels. Thirdly, the implementation of the ABM is adapted to distinguish direct and indirect effects.

To determine the average effects of heat stress on labor productivity per industry and quarter, we have combined the productivity data with data on the regional economic structure. In the ABM we included these average effects by expanding the production function. The scenario-related reduction in labor productivity is based on the shock implementation developed by Poledna et al. (2018):

$$\mathrm{Y_i}\,(\mathrm{t}) = \min\left(\mathrm{Q_i^s}\,(\mathrm{t}),\mathrm{N_i}\,(\mathrm{t})\,\alpha_{\,\mathrm{i}}\,(\mathrm{t})\,(1-\gamma_{\,i}\,(\mathrm{t}))\,,\mathrm{K_i}\,(\mathrm{t}-1)\,\kappa_{\,\mathrm{i}}\,(\mathrm{t})\,,\mathrm{M_{(i)}}\,(\mathrm{t}-1)\,\beta_{\,\mathrm{i}}\,(\mathrm{t})\right)$$

In each period *t*, firm *i* in industry *s* produces output *Y* (in real terms) by combining labor *N*, intermediate goods/services and raw material *M*, and capital *K*. We assume a production function with Leontief technology. All intermediate goods, labor, and capital, respectively, represent upper limits to production. α, β, and κ are the productivity coefficients for labor, intermediate inputs, and capital, respectively. Furthermore, production is limited by the firm's supply choice $\mathrm{Q_i^s}$.

Our modifications are captured by the term $(1-\gamma_{\,i}\,(\mathrm{t}))$. γ_i is an industry-specific shock to labor productivity due to heat stress. The assumptions behind this modification are that (1) the reduction in labor productivity is seasonal, permanent and occurs every year, as described in the Data section, (2) there is no compensation via longer working hours, and (3) there are no adjustment reactions in work organization (e.g., no shift of work into cooler seasons, no additional air conditioning in the production facilities). Since there is no substitution between the production factors, the effects on labor productivity are directly transferred to output with the respective weight of the input factor labor.

We assume firms to keep their stock of capital and input goods at a desired target level corresponding to the stocks in the initial period ($t=0$). However, a reduction in production output results in less depreciation of capital and less use of intermediary inputs. Therefore, this is to be counteracted by decreased investments and decreased purchases, respectively. Details on the formal representation of these changes are described in the supplementary material.

The total effects of the reduced labor productivity are broken down into direct (initial) and indirect (follow-up) effects. For each quarter and industry, we define the direct loss as the difference between the productive outputs at full and at heat-induced reduced labor productivity. All other effects are considered indirect. The latter can be caused, e.g., by input-output linkages, income effects, or carry-over effects from previous periods.

With these adaptations, we can simulate the detailed effects of changes in labor productivity through projected climatic changes. Our method provides a blueprint for other EU countries and the model can be extended to climate change impacts such as floods (Poledna et al. 2018), droughts, storm and hail damage, and forest fires. For further details concerning economic, population, and labor growth pathways and underlying assumptions, see Poledna et al. (2023).

3.2 Data

To estimate the industry-specific changes in labor productivity due to climate change in the future, appropriate modeling of WBGT is required, as this is necessary for the assessment of heat stress in the workplace. As this heat indicator is not used in many scientific fields, it is not a standardized part of climate models and is not found in conventional temperature forecasts, especially at a regional level. The data for the predicted change in WBGT was therefore extracted from the www.ClimateCHIP.org (Climate Change Health Impact and Prevention) Web platform (ClimateCHIP 2024). Data is provided for the midpoint of the projections of two global climate models within the SSP3-7.0: the USA NOAA model GFDL-esm4 (GFDL) and the UK met office model UKesm1-0-LL. On the sociopolitical side, the SSP3-7.0 describes a future that is characterized by regional rivalries and growing national protectionism resulting from limited resources and geopolitical tensions. For the climate, it indicates a radiative forcing of 7 W/m^2 until the end of the century, filling a gap between the Representative Concentration Pathways RCP6 and RCP8.5, and resulting in a global surface temperature increase between 2.8 °C and 4.6 °C, with best estimations lying at 3.6 °C (Intergovernmental Panel on Climate Change (IPCC) 2023). The data was aggregated to 0.5×0.5 degree grid cells and bias corrected by the Potsdam Institute for Climate Impact Research (PIK) using the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP). With the Workplace Heat Effects Assessment Tool (WorkHeat) the www.ClimateCHIP.org Web platform provides further insight into productivity losses for the work intensities low, medium, and high under WBGT indoor and outdoor based on the exposure response functions developed by Kjellstrom et al. (2018). These are fitted continuous functions integrating the epidemiological data from Wyndham (1969) and Sahu et al. (2013) as well as the reference values implied in ISO 7243 (Kjellstrom et al. 2018). This allows the prediction of productivity losses to be extracted for the aggregated grid cells and two, moderate and high, WBGT scenarios. These are based on climate projections for the periods 2011–2040 and 2041–2070, respectively. The data give the monthly mean productivity loss throughout a year. Out of the monthly values we constructed an average for each quarter to be able to implement it into the ABM, which uses quarters as simulation period. The scenario 2 (“moderate”) based on the climate projection for 2011–2040 represents current and near future effects of heat stress in Austria. Scenario 3 (“high”) is intended as a worst-case scenario and assumes that the WBGTs predicted by ClimateCHIP for the period 2041–2070 can occur earlier. Thus, we want to account for a possible faster progressing climate crisis and extreme weather events as well as to investigate future developments with increasing temperatures. The moderate and high scenarios are compared with a baseline scenario, which assumes no climate change (scenario 1 “no climate change”).

3.2.1 Industry-disaggregated work intensity

To evaluate the industry-specific impact of heat exposure on labor productivity we assign three different work intensities light, moderate, and heavy, as indicated by the exposure-response functions from Kjellstrom et al. (2018) in the Workplace Heat Effects Assessment Tool (WorkHeat) and provided by the extracted Data from www.ClimateCHIP.org, to the NACE industries in Austria. For each industry, we also assess whether the activity takes place mainly in the sun (outdoor) or in the shade (indoor). In case of indoor activities, assumptions regarding the degree of automatization and climatization were considered for assigning the respective work intensity. Recognizing the inherent approximation involved in this cross-application of standards, our methodology is underpinned by insights drawn from earlier studies regarding this topic. As our paper includes the effects of heat stress on labor productivity in various industries, the categorizations used in the literature were expanded and refined. Table 1 shows a sample of the assigned industry-specific labor intensities for a broad spectrum of industries including more severely affected ones like construction and crop and animal production (Sun, heavy), as well as moderately affected industries like the manufacture of chemicals (Shade, moderate) and less affected industries like retail trade and education (shade, light).

A comparison of different classifications of work intensities on an industry-level drawn from the literature is described in the supplementary material. We use the categorization made by Stalhandske et al. (2022) for a sensitivity analysis to compare it with our own considerations. This gives us two different estimates of labor intensity in many of the relevant industries, especially in manufacturing. We use both estimates to examine the estimations made and thus draw attention to the effects of the degree of technologization and possible adjustment measures within the respective industries. The results are described in the supplementary material. Since the methods and data applied could be used for a comparison between European countries in subsequent studies, this is particularly interesting for an evaluation of the influence of a country's economic structure on the macro-economic impact of heat stress. A comprehensive list of our classification of the NACE Rev.2 industries and the work intensity in degrees of 200 W (light), 300 W (moderate), and 400 W (heavy), as well as the categorization in indoor and outdoor work, can be found in the supplementary material.

3.2.2 Regional economic structure

Anticipated heat-related impacts differ in terms of both regions and industries. To estimate average national impacts on labor productivity on an industry level, we consider the regional economic structures of the different Austrian regions. We rely on employment data due to data availability reasons and because the effects of a decline in labor productivity correspond

Table 1 Classification of work intensity, sun exposure, and productivity loss for exemplary industries. A heat scenario for 2041–2070 has been assumed

NACE industries		Sun exposure	Work intensity	Productivity loss			
				Q1	Q2	Q3	Q4
G47	Retail trade, except for motor vehicles and motorcycles	Shade	Light	0.00%	0.03%	0.22%	0.00%
M71	Architectural and engineering activities; technical testing and analysis	Shade	Light	0.00%	0.03%	0.22%	0.00%
P85	Education	Shade	Light	0.00%	0.03%	0.22%	0.00%
C20	Manufacture of chemicals and chemical products	Shade	Moderate	0.00%	0.14%	0.77%	0.00%
C24	Manufacture of basic metals	Shade	Heavy	0.00%	0.26%	1.25%	0.00%
R93	Sports activities and amusement and recreation activities	Sun	Light	0.00%	0.18%	0.75%	0.00%
E37-39	Sewerage, waste management, remediation activities	Sun	Moderate	0.00%	0.46%	1.72%	0.00%
A01	Crop and animal production, hunting, and related service activities	Sun	Heavy	0.00%	0.71%	2.51%	0.00%
F	Construction	Sun	Heavy	0.00%	0.80%	2.73%	0.00%

more closely to the number of employed persons in a region than to other economic indicators. Since our goal is to provide a methodology which is readily transferable to other countries, we primarily rely on Eurostat data. 2019 was used as the reference year, because the ABM already covers the period up to 2019 and data from the subsequent years, which are already available, might lead to biased results due to the COVID pandemic. To get sufficiently disaggregated data in terms of industries and regions, we applied the following procedure: (1) The distribution of employees per industry across the NUTS 2 regions were initially taken from the Labor Force Survey (Eurostat 2024b) for the NACE sections A, K and O-S. For the NACE sections B-J and L-N we used the structural business statistics (Eurostat 2024d), because it offers a more detailed structure of industries. This is particularly critical for the manufacturing industry (NACE C), which includes industries with very heterogeneous work characteristics.[3] (2) The further breakdown to NUTS 3 regions was then carried out using employment data from the national accounts (Eurostat 2024c). To our knowledge this is the only data source readily available for NUTS-3 regions, but only offers a very broad economic structure of 7 industries.[4] (3) As no EU-wide employment data is available below NUTS 3 level, we used population data for the local administrative units for a further breakdown (Eurostat 2019a). In doing so we implicitly assumed that economic activity is distributed within the NUTS 3 regions much like the population. Obviously, this is not always true, but still more accurate than assuming equal distribution and we avoid allocating too many jobs to very sparsely populated Alpine regions. (4) The local administrative units are assigned to the ClimateChip regions based on centroids (Eurostat 2024e). The estimated shares of employees by local administrative units for each industry can now be used to calculate a weighted average labor productivity loss for each industry, which serves as an input for the ABM. Selected sectors are also listed as examples in Table 1. An exhaustive list is provided in the supplementary material.

As described above, EU-wide data on regional economic structures are not overly detailed. To check whether this has a significant influence on the results and to validate our results for the application case Austria, we rerun the model using more detailed data from Statistics Austria. The results are available in the supplementary material.

4 Results

The output of the ABM simulations allows us to investigate both macroeconomic and industry-level indicators and to contrast direct and indirect effects of heat-induced productivity losses. Figure 1 shows the growth paths of macroeconomic indicators such as the real values of the gross domestic product (GDP), gross value added (GVA), capital formation (including gross fixed capital formation and changes in inventories), consumption of private households as well as foreign trade (exports and imports). We compare the results for the baseline scenario without heat stress (1) and the scenarios with moderate (2) and high (3) heat stress (see Fig. 1). We use these two heat stress scenarios to highlight different dimensions of its

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[3] NACE sections T and U, which are relatively small and rather isolated from the rest of the economy, are not covered by the ABM. Several confidential values in the data were estimated based on appropriate assumptions.

[4] We are aware that there are certain differences in the employment data depending on the data source used. As we are primarily interested in regional shares by industry, this should not cause any issues.

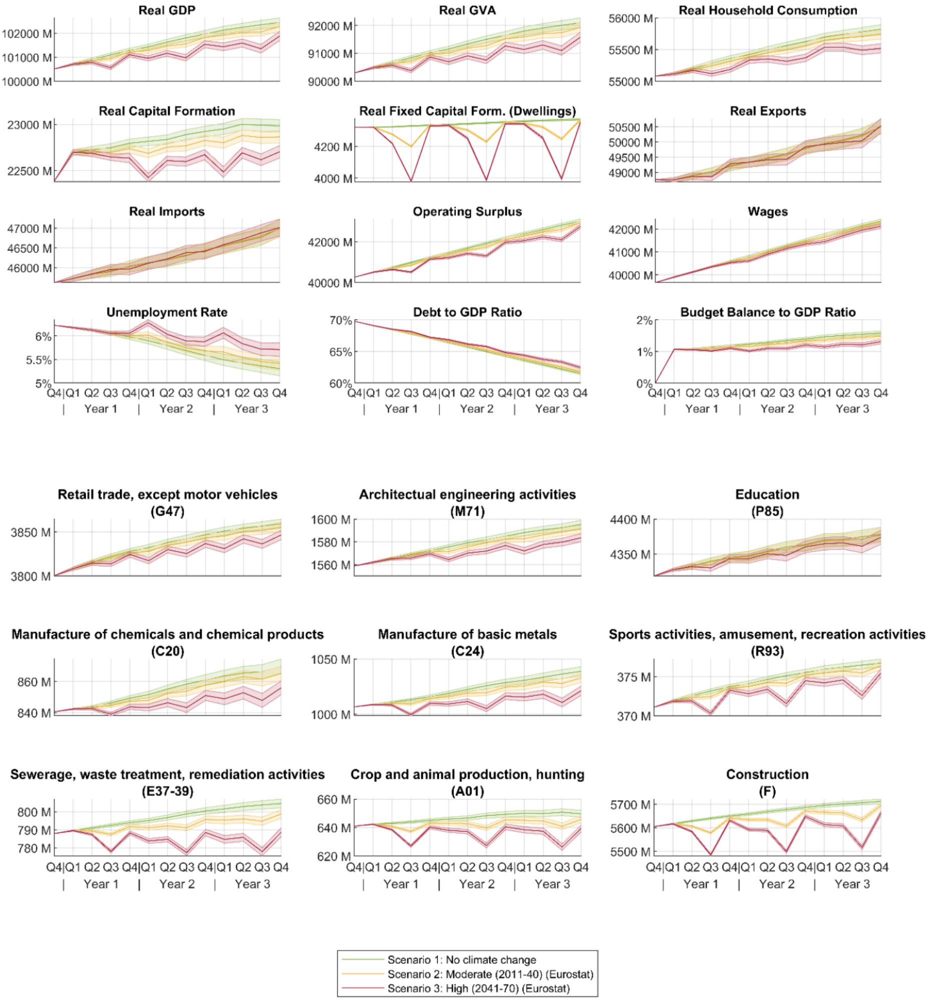

Fig. 1 Effects of heat stress on macroeconomic variables and the gross value added of selected industries in Austria. The bold lines show the mean over 500 Monte Carlo runs for each quarter. Shown are also the 95% confidence intervals for the mean

impacts on labor productivity. All presented economic trends reflect the loss in productivity in relation to the baseline scenario. In the description below we focus on the difference between the high and the baseline scenarios. The developments related to the moderate scenario are depicted in the figures below. The ABM simulations run over a period of three years (twelve quarters), starting from 2020Q1.

The following observations can be made from the results of the analysis: In the high scenario (3), real GDP is by 0.7% or 2,92 bn. Euro below the baseline scenario in the third year, with a peak of minus 1.0% in the third quarter. Overall, the gap widens over the observed three years. Total real GVA follows a similar path as GDP[5]. Hence, both indicators remain

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[5] GVA and GDP only differ by net production taxes, i.e., production taxes paid by companies minus subsidies to the company sector.

generally below the growth path of the baseline scenario (1), which means that heat stress affects the economic performance negatively throughout all scenarios. GDP and GVA, along with several other indicators, exhibit a seasonal pattern. The main reason is the seasonality of labor productivity losses, which– intuitively and by assumptions underlying the scenarios– are highest in Q3 (July to September), but virtually zero in Q1 (January to March) and Q4 (October to December). Thus, there is always a large gap between baseline scenario 1 (no heat-related effects) and the shock scenario 3 in Q3, whereas in Q4 the gap is induced by indirect effects from the previous quarters. In the first year of the simulation period those indirect losses are rather small, while in later years they constitute a growing portion of the total gap to the base scenario (see below in Fig. 2), as indirect effects accumulate.

The individual components of real GVA show remarkable differences: Gross operating surplus (minus 1.0% in the third year in the high scenario (3) compared to the baseline (1), with a maximum of minus 1.7% in the third quarter) is affected by heat stress to a larger extent than wages (minus 0.5% in the third year). This is due to the price and quantity setting procedures by firms. Firms absorb the productivity declines due to heat stress with a decreased operating surplus because neither do they pass on the productivity losses to the prices they charge, nor do they decrease the wages they pay to reflect reduced output per hour worked to compensate for their losses in revenues. Production reductions induce a range of indirect effects, such as a decrease in demand for intermediate products in the production process, lower investment, and respective impacts on employment and wages. This also means that the reduction in aggregate wage income appears with a time lag, which is

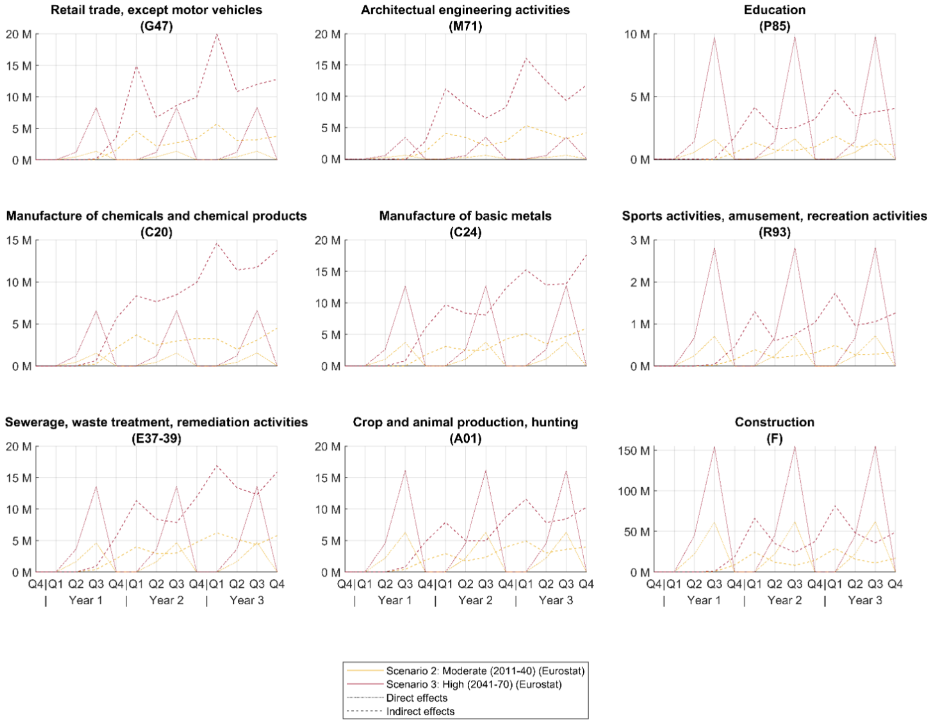

Fig. 2 Contrast of direct and indirect loss in gross value added of selected industries in Austria. Shown are the average results of 500 Monte Carlo runs

why the largest gaps– countercyclical to the initial productivity shocks - occur in the winter months, reaching minus 0.7% in the first quarter of the third year. The same holds for the unemployment rate, which is 0.6% points higher in the high (3) scenario compared to the baseline in the first quarter of the third year. On average, the increase in the unemployment rate amounts to 0.4% points in the third year.

Accordingly, as not all effects are passed on directly from firms to employees, real consumption of private households is also affected to a more limited extent. The decrease of this indicator compared to the baseline scenario amounts to 0.4% in the third year, peaking at 0.5% in the autumn quarter (fourth quarter). In line with the arguments above, this is because labor income is affected by the productivity losses with a time lag. In our model, consumption is a direct function of disposable income. Hence, if wages fall a lot less than total income, consumption remains more stable than GDP as labor productivity falls.

The government budget is also adversely affected. In the high scenario (3) the budget balance to GDP ratio is 0.3% points below the baseline scenario in the third year. Growth of foreign trade does not show any considerable changes in the high compared to the baseline scenario. Exports are slightly lower (minus 0.1% in the third year). This decrease can be explained by the productivity loss resulting from heat stress, especially in the summer months. Imports, in turn, are higher (approximately plus 0.1% in the third year).

On the industry level (Fig. 1 lower part), industries like mining and quarrying (minus 6.2% in the third year of the simulation period), manufacture of coke and refined petroleum products (minus 3.5%), forestry, and logging (both minus 3.2%) and agriculture (minus 2.3%) show large effects, because they are characterized by heavy work, exposure to sun and/or operate in regions that are strongly exposed to heat. In absolute terms, construction is by far the most affected sector, with an effect on value added of nearly minus 0.4 bn. Euro in the third year.

Other industries are by far less affected by heat stress, such as manufacture of machinery and equipment, manufacture of electrical equipment, and many of the service industries, including trade and public administration. The seasonal effects are also often less pronounced in these industries because they are mainly indirectly affected by heat stress through reduced demand for intermediate goods. Some industries even react with a delay and therefore have a countercyclical impact. This has different reasons: It is either because they largely depend on an aggregate economic variable like employment income (e.g., retail trade or real estate activities), which reacts with a lag to the initial shock in the economy, or they adjust their production with a lag as a result of direct losses by important customers of their goods (e.g., manufacture of other non-metallic mineral products, which is a major supplier for the construction industry).

To further explore the composition of the total effects we distinguish direct (initial) and indirect (follow-up) effects (Sect. 3.1). This analysis is useful, as due to indirect effects, even industries that do not experience large reductions of labor productivity can be hit hard.

Figure 2 illustrates this distinction for the GVA of selected industries. The y-axis displays the gap between the base scenario (1) and the scenarios with heat stress arising from direct and indirect effects. In the first year, the direct labor productivity effects dominate in all industries, and since we assume the shock to occur annually, the direct effect remains about constant every year. Indirect effects on the other hand grow over time. In industries with heavy work intensity and exposure to the sun (e.g., construction or agriculture (crop and animal production as well as hunting) see Table 1), the direct effects have a high share,

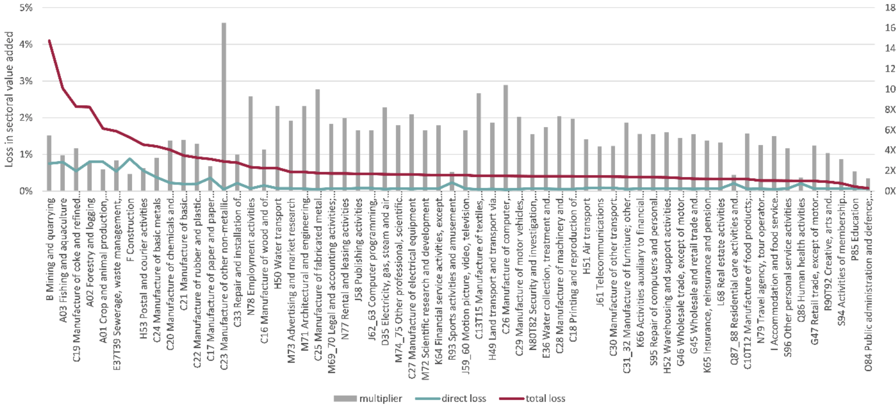

Fig. 3 Loss in real gross value added per industry: direct and total effects (3-years aggregate)

whereas other industries (like retail, architectural services, or mining and quarrying) are mainly indirectly affected. Overall, in the first year around three quarters of the total GVA effect can be considered direct and one quarter indirect, while in the second year, this relation is already inverted. In the third year of the analysis, the direct impact is down to around 21% of the total versus 79% indirect effects.

Figure 3 further analyses the relation between direct and indirect losses in GVA on the industry level. The red line shows the total loss in GVA by industry, now aggregated over the entire period of three years, in the high scenario (3) in relation to the baseline scenario (1). The blue line marks the direct (initial) loss. The gap between both lines represents the indirect effects. The gray bars indicate the multipliers by which the direct loss per industry is increased due to the indirect effects in the economy.[6] The direct loss multiplied by the respective multiplier results in the total productivity loss due to heat stress. The sector "manufacture of other non-metallic mineral products" shows the highest multiplier as it is a major supplier of the construction industry. Its direct GVA effect due to reduced labor productivity is rather small (minus 0.05% in total over three years), but indirect effects result in total effects of minus 0.81%, which is higher by a factor of 16.5. Sectors like retail trade or accommodation and food services also feature relatively high multipliers, primarily because they are sensitive to income and hence consumption declines. On the other hand, for industries with high initial labor productivity impacts (e.g., construction or agriculture) and/or limited linkages to severely affected industries, the multipliers are typically smaller, e.g., only 1.3 for public administration and around 1.7 for construction.

As described above, EU-wide data on regional economic structures are not overly detailed. To check whether this has a significant influence on the results, we rerun the model by using more detailed data from Statistics Austria. The results display no substantial differences on the macro level and certain but limited differences for specific sectors. The categorization of the different NACE industries regarding work intensity and work environment has a larger but still limited effect on the results, as shown by the sensitivity analysis. For example, using Stalhandske et al. (2022) results in a loss in real GDP in the high scenario (3) compared to

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[6] The multiplier refers to the period of three years. If a longer period is considered, the share of indirect effects increases and the multipliers are higher.

baseline of 1.0% over the third year with a peak loss of 1.3% in its third quarter. Details are available in the supplementary material. Thus, our analysis for Austria based on Eurostat data can be seen as a blueprint methodology that can be enlarged for comparative studies on heat stress and labor productivity for other EU countries.

5 Discussion

To our knowledge, the macroeconomic effects of heat stress have not been studied on a comparable level of detail in the existing literature. The only other available study for Austria previously mentioned (Urban and Steininger 2015; Steininger et al. 2016) is restricted to manufacturing and trade using a CGE model, while our study considers all industries using an ABM. Since our methodology does not compute household welfare indices, a comparison in terms of GDP is more appropriate. Compared with their high range climate scenario, the total cumulative output losses of all industries for our most pronounced scenario are higher, with about 0.5% of GDP on average within the first three years. The GDP losses increase over time and amount in total to 6.0 bn. Euro over three years and 2.9 bn. in the third year alone due to productivity losses induced by heat stress and the macroeconomic repercussions. It is difficult to compare the calculations made by Steininger et al. (2016), as the time frame under consideration and the underlying values as input for the CGE are different. As a reference scenario, Steininger et al. (2016) take exogenous assumptions for the development of economic growth, demographic change etc., that are in line with the SSP2 scenario and calculate the average effects on a time frame of around 30 years. However, the multipliers regarding the ratio between direct heat-induced labor productivity losses and total economic effects including indirect effects are of a similar scale. These results show that our results are in line with the extant literature while expanding the underlying methodology regarding the additional level of economic detail captured in our ABM analysis and empirical database.

Labor productivity losses induced by heat stress are only one of many channels through which the climate crisis affects the economy. For the overall climate damages for Austria, several studies exist to which our results can be compared. Building on previous work (Steininger et al. 2016; 2015), the estimates of Steininger et al. (2020) for total climate damages in Austria provide a lower boundary of at least 2 billion Euro per year. Around 2030, these climate damages are expected to range between 3 and 6 billion Euro annually. Around 2050, they are forecasted to amount to between 6 and 12 billion Euro per year (Steininger et al. 2020). These total numbers of expected climate damages provide a further framing for the results of our study.

In a CGE model-based study, Bachner and Bednar-Friedl (2019) analyze the impacts of climate change on public budgets in Austria. In their scenario without specific budgetary balancing by introducing additional taxes or other sources of government revenue, which is the most comparable to our analysis, they find a cumulative reduction of Austrian GDP of 0.2%, as well as a reduction of government revenues of a cumulative 0.3%. Since the CGE model seems to operate with a balanced budget constraint, public expenditures also must be reduced by 0.3%. Since some budgetary items in their analysis are increased by expected climate change impacts, the level of public services must be reduced by 1.4% to accommodate the reduced revenues and increased other expenditures. The specific effects of climate damages and climate risk on the Austrian budget have also been summarized in a recent study by the Austrian Institute for Economic Research (Köppl and Schratzenstaller 2024). Here, the authors, referring to Bachner and Bednar-Friedl (2019), mention increased climate adaptation-related expenditures of about one billion Euro annually in the period 2014 to 2020. In regard to future estimates of climate adaptation related public expenditures, Steininger et al. (2020) find increased expected expenditures of up to approximately 1.7 billion Euros annually in the period 2021–2030 and approximately 2.4 billion annually in 2031–2050.

One of the main aims of this paper is to provide a blueprint for the economic analysis of heat stress and labor productivity. Therefore, the transferability of the method to other geographical areas is of specific concern. While the applicability to other EU-countries is generally possible, there are country-specific characteristics that should be accounted for. The characteristics of different work environments in industries might need to be adapted when creating a classification of heat stress. An example could be manufacturing– while manufacturing tends to be highly automatized in Austria, there might be a higher degree of physical work elsewhere.

The macroeconomic impact would be more pronounced if sick leave and higher incidence of accidents were included. Conversely, the impact could also be more limited depending on adaptation measures that may have a cushioning effect on the macroeconomic losses we calculated. In this context, suggested measures include shifting work from daytime to early morning and evening hours or from summer to other seasons, which is particularly crucial in the construction sector, where under some circumstances, the effect on the timing of working hours might be stronger than the effect on the overall level of economic activity. Furthermore, technological progress can be used, where feasible, via provision of air conditioning systems or ventilation as well as through special clothing. Moreover, expanding employee protection regulations to include aspects like mandatory shadow breaks and water supply at work would be cost-neutral for the government and could reduce the real GDP loss of 0.7% we projected for the third year in the most severe scenario. At the same time, considering the combination of intensifying heat and shortages of skilled workers, it should be in the interest of companies to provide work environments that enable productive work despite the heat, even without additional regulations being implemented. These suggestions, while not exhaustive, are based on the presented literature and offer a framework that needs to be refined and expanded based on specific regional contexts.

6 Conclusion

In this paper, we have applied an ABM of the Austrian economy to quantify the macroeconomic effects of labor-productivity losses induced by heat stress. According to our results, the macroeconomic impacts are economically significant, but manageable in the short-term, particularly when compared to the GDP losses caused by the great financial crisis or the COVID-19 pandemic. This, however, only holds true for this specific case study of Austria and the near future. Due to the complexities of climate-change related economic impacts, it is difficult to include all possible channels in a single model. Here, we focused on heat stress and its macroeconomic impacts via labor productivity losses without adaptation measures and technological change.

In other geographical areas, larger impacts of heat stress than those analyzed in this paper are expectable. We focused on Austria but provided a blueprint for other European countries. The ABM used here is based on Eurostat data. At least for all 27 EU member states, the Eurostat database, and the Figaro input-output tables, also published by Eurostat, provide sufficiently detailed data to construct similar models, and to conduct similar analyses and country comparisons.

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Author contributions CK: Conceptualization, Methodology, Writing - Original Draft, Writing - Review and Editing, Project Administration; KW: Conceptualization, Methodology, Writing - Original Draft; TC: Conceptualization, Writing-Original Draft, Writing-Review and Editing; NF: Writing - Review and Editing, Formal Analysis, Visualization; MK: Writing - Original Draft, Data Curation; EL: Conceptualization, Methodology, Writing - Original Draft; LM: Writing – Original Draft, Writing - Review and Editing, Data Curation; KP: Conceptualization, Methodology, Writing – Original Draft, Writing - Review and Editing; LU: Conceptualization, Methodology, Writing - Original Draft, Data Curation; HZ: Conceptualization, Methodology, Formal Analysis, Data Curation, Writing - Original Draft, Writing - Review and Editing, Visualization; MM: Writing – Original Draft, Writing - Review and Editing; SP: Conceptualization, Writing - Review and Editing, Formal Analysis.

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Data availability For the calculation of the industry-specific labor productivity losses, the raw data and preparation script are available as supplementary data at https://doi.org/10.5281/zenodo.13880369. The resulting data is available in the supplementary material section of the article. The ABM used here is based on Eurostat data. At least for all 27 EU member states, the Eurostat database, and the Figaro input-output tables, are published by Eurostat. The agent-based model is available at https://doi.org/10.5281/zenodo.7271552. The modifications made to the model are described and formulated in the supplementary material.

Declarations

Competing interests The authors have no competing interests that could have influenced the results reported in this paper.

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