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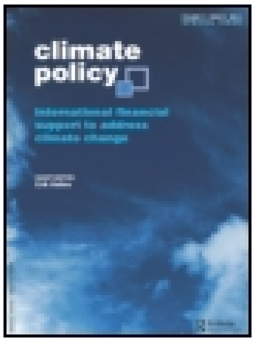

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Upholding labour productivity under climate change: an assessment of adaptation options

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ABSTRACT
Changes in labour productivity feed through directly to national income. An external shock, like climate change, which may substantially reduce the productivity of workers is therefore a macroeconomic concern. The biophysical impact of higher temperatures on human performance is well documented. Less well understood are the wider effects of higher temperatures on the aggregate productivity of modern, diversified economies, where economic output is produced in contexts ranging from outdoor agriculture to work in air-conditioned buildings. Working conditions are at least to some extent the result of societal choices, which means that the labour productivity effects of heat can be alleviated through careful adaptation. A range of technical, regulatory/infrastructural and behavioural options are available to individuals, businesses and governments. The importance of local contexts prevents a general ranking of the available measures, but many appear cost-effective. Promising options include the optimization of working hours and passive cooling mechanisms. Climate-smart urban planning and adjustments to building design are most suitable to respond to high base temperature, while air conditioning can respond flexibly to short temperature peaks if there is sufficient cheap, reliable and clean electricity.

Key policy insights

- The effect of heat stress on labour productivity is a key economic impact of climate change, which could affect national output and workers' income.
- Effective adaptation options exist, such as shifting working hours and cool roofs, but they require policy intervention and forward planning.
- Strategic interventions, such as climate-smart municipal design, are as important as reactive or project-level adaptations.
- Adaptation solutions to heat stress are highly context specific and need to be assessed accordingly. For example, shifting working hours could be an effective way of reducing the effect of peak temperatures, but only if there is sufficient flexibility in working patterns.

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Heat stress; heat and labour productivity; climate change adaptation; climate-resilient development

1. Introduction

Labour productivity is an important driver of economic success. Economists devote a great deal of attention to understanding, measuring and enhancing productivity (see e.g. Bosworth & Collins, 2008; Jorgenson, Ho, & Stiroh, 2008; Van Ark, O'Mahoney, & Timmer, 2008). The potential impact of climate change on labour productivity is therefore an important economic concern. Any changes in labour productivity will have a direct

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effect on national output and individual incomes. In low-income countries it could jeopardize poverty reduction strategies and other sustainable development goals.

There is growing evidence that the labour productivity effects of climate change could be substantial. Rising temperatures may increase labour productivity in regions with low baseline temperatures (Hallegatte et al., 2016; Heal & Park, 2016), but in most countries – especially lower income countries – and at the global scale the effect is likely to be negative (e.g. Burke, Hsiang, & Miguel, 2015; Kjellstrom, Kovats, Lloyd, Holt, & Tol, 2010; UNDP, 2016). Already today, the aggregate national-level effect of heat on economic output is on a par with other health-related impediments to labour productivity (Evans-Lacko & Knapp, 2016; Goetzel et al., 2004; Vivid Economics, 2017).[1] Productivity losses could rise rapidly once certain temperature thresholds are breached. According to the IPCC fifth assessment report global mean temperatures by 2100 are likely to be at least 1.5°C higher than during 1850–1900 and under some scenarios more than 5°C higher (IPCC, 2014), with varying increases for individual regions and a higher incidence of temperature spikes in most places.

The empirical relationship between heat stress and the task productivity of individual workers is reasonably well-known and robust, although there are different approaches to quantifying it (see e.g. Lemke & Kjellstrom, 2012). Occupational heat exposure is caused by several factors, including air temperature, humidity, wind speed, exposure to direct sunlight, clothing and the intensity of work being undertaken (Heal & Park, 2016). The heat exposure threshold above which task-based productivity declines will depend on each of these factors and on the individual's level of acclimatization to high temperatures.

Many of the contextual factors on which the heat-productivity relationship depends, such as clothing or the time when a task is performed, can be influenced through private and public decisions. That is, labour productivity effects can be reduced through adaptation. The main unknown in quantifying the economic impact of higher temperature is not the biophysical relationship between heat and worker productivity, but the socio-economic and environmental context in which productive tasks are performed.

The purpose of this paper is to summarize and synthesize what we know about the scope for such adaptation. The paper contains a concise new exposition of the merit of different adaptation options for policy makers and policy-oriented researchers. It identifies and assesses the main adaptation options that are available to public and private decision makers to alleviate heat-related productivity effects. The focus is on adaptation strategies in a development context, but the insights are valid more broadly.

The paper contributes to the literature in two ways. First it maps in a novel way the solution space of adaptation options and considers who the primary agent of change would be for different types of adaptation solutions. To maximize its policy impact, the paper adopts a decision-making framework for adaptation that explicitly acknowledges the importance of local contexts and the high levels of uncertainty about future climate regimes. These two factors are defining features of adaptation decision making (Fankhauser, 2017). Second, the paper provides a high-level review of the impact of high temperatures on labour productivity and the possible adaptation responses to alleviate this impact, complementing existing surveys with a policy audience in mind.

Specifically, the paper assesses 17 concrete adaptation measures, drawn from a long list of over 30 responses according to a set of evaluation criteria. The exact merit of individual options – or, in an economic appraisal framework, their benefit–cost ratio – will depend on context. There are different adaptation solutions for indoor and outdoor work, or to address higher base temperatures and short-term temperature peaks. Some adaptations (such as different working hours) may be constrained by cultural factors, others (such as air conditioning) require access to cheap, clean electricity. Decisions also depend on the nature of the future climatic changes, and at the local scale many of the decision-relevant parameters – such as temperature peaks, wind regimes, seasonal and diurnal variations – remain largely unknown.

The paper provides a new conceptual framework that can help decision makers identify suitable options. The framework sets out the main factors that will determine the value for money of adaptation options in a specific setting and the importance of uncertainty around the evolution of climate change. It emphasizes the value of measures that increase flexibility in response and/or which would be 'low-regrets' – that is, they are likely to be beneficial to implement in any future state of the world.

While the importance of local contexts prevents a general ranking of adaptation measures, there are rules of thumb as to when particular solutions are likely to provide value for money. In general, behavioural measures such as changing working hours to avoid the hottest parts of the day/year, and passive adaptation options such as regular breaks, are likely to be effective in dealing with temperature peaks, especially where these are most keenly felt by high-intensity outdoor workers. Our analysis suggests that optimizing working hours is perhaps the adaptation measure with the largest systemic impact, if it can be deployed at national scale. Adjustments to building design are most suitable for a shift in base temperatures, while air conditioning can also respond flexibly to short temperature peaks. However, it bears repeating that the merit of energy intensive solutions, like air conditioning, depends on the cost, carbon content and accessibility of energy.

The rest of the paper proceeds as follows. Section 2 reviews the literature on temperature and labour productivity. An understanding on how climatic factors affect the performance of workers provides the basis from which adaptation options can be designed. Section 3 offers a broad mapping of the adaptation landscape and identifies the most important measures worthy of further analysis. Section 4 introduces an evaluation framework to help decision makers assess the value-for-money of these key options. Section 5 contains insights on 17 prominent adaptation options that emerge from this framework. Section 6 concludes.

2. Temperature and labour productivity

The literature distinguishes three mechanisms through which heat affects the total productivity of the labour force (Heal & Park, 2016): (i) labour supply, that is, the total hours that individuals choose to work, (ii) labour effort, that is, the amount of effort workers choose to expend while at work, and (iii) labour productivity, that is, the degree to which workers' effectiveness is degraded while at work.

This paper is concerned with the last of these effects. We start with a brief synopsis of the relevant literature. The literature review was carried out using keyword searches in *Publish and Perish*, a software tool that retrieves and analyses citations of both grey and peer-reviewed publications from Google Scholar and Microsoft Academic Search. We used the Publish or Perish software, which enables rapid and broad reviews of existing literature, in tandem with author-identified literature to ensure that the targeted literature synopsis did not omit any key references academic or grey literature. The purpose was not to conduct a systematic review of all the evidence. Rather, the objective was to inform the scope and effectiveness of different adaptation options. Other prominent literature reviews of the link between heat and labour productivity include Hallegatte et al. (2016), Kjellstrom et al. (2016) and Heal and Park (2016). The majority of the available studies examine this relationship in a specific national-sectoral context, for example looking at one particular industry or context in a specific country, or synthesizing existing studies within these contexts (see Table 1).

All studies find substantial reductions in labour productivity for temperature increases above a certain threshold. While the exact threshold and the degree of impact vary across studies, they indicate that once a threshold value is breached, increasing temperatures are associated with decreasing labour productivity, and that such decreases increase with the temperature level.

The insights of these empirical studies can be combined into a continuous relationship between labour productivity and heat exposure. These response functions typically measure productivity loss either as a percentage value of full productivity, or as percentage productivity loss relative to full productivity. The most common measure of heat exposure is the 'Wet Bulb Globe Temperature' (WBGT) index. The WBGT is a weighted average of different heat measures (wetbulb, black globe and air temperature) that reflects the combined effect of temperature, humidity, sunlight and wind on the performance of athletes, soldiers and outdoor workers (see for example, Epstein & Moran, 2006; Lemke & Kjellstrom, 2012). The WBGT index is not the only measure of heat exposure or heat stress. Alternatives, which also reflect factors such as acclimatization, include the Excess Heat Factor (Hatvani-Kovacs, Belusko, Pockett, & Boland, 2016), surveys and self-assessments (Zander, Moss, & Garnett, 2017) or associations between hospital records and worker compensation and temperature levels (Xiang, Bi, Pisaniello, & Hansen, 2014). However, WBGT is a user-friendly, commonly used and widely understood method for assessing stress in hot thermal environments (D'Ambrosio Alfano, Palella, & Riccio, 2012).

Figure 1 shows four sets of response functions, each of which includes a number of functions for different levels of work intensity. Prolonged exposure to high temperature may lead to further reductions in productivity, which is not captured in the response functions. Similarly, the response functions do not take into account

Table 1. Empirical estimates of the effect of heat on individual productivity.

Study	Context	Findings
Adhvaryu, Kala, and Nyshadham (2016)	Effect of indoor temperature on manufacturing productivity, India	Manufacturing worker efficiency declines on hotter days due to reductions in task productivity rather than increased absenteeism
Cachon, Gallino, and Olivares (2012)	Impact of heat stress on automobile manufacturing plant output, United States of America	Hot days are associated with lower output: on average, a week with six or more days of heat exceeding 90°F (32°C) reduces production in that week by 8%
Graff Zivin and Neidell (2014)	Effects of temperature on workers' time use (to work, leisure) in the United States of America, for overall workers and comparing 'high risk' sectors (agriculture, construction, manufacturing, transportation, utilities) and 'low risk' sectors (all others)	At temperatures above 85°F (29°C), workers in high risk industries reduce daily output by as much as one hour, reallocate time to indoor (air conditioned) leisure; No impact for low-risk sectors
Heal and Park (2013)	Examine the general labour productivity relationship with temperature using country-level data, 1950–2005	Hotter-than-average years lead to lower output in hot countries, but lead to higher output in colder countries (as hot years are associated with increased productivity) – the relationship is around 3% or 4% change in labour productivity per °C variation
Hsiang (2010)	Impact of temperatures and tropical cyclones on agricultural and non-agricultural production in 28 Caribbean countries, 1970–2006	On average, a 1°C temperature increase is associated with a 2.4% reduction in non-agricultural production and a 0.1% reduction in agricultural production (after controlling for the influence of tropical storms)
Houser et al. (2014)	Review of previous literature on labour productivity effects of heat stress	Higher temperatures lead individuals to spend more time indoors, take more frequent breaks, reduce cognitive capacity and endurance
Nag and Nag (1992)	Experimental evidence of effect of heat stress on women doing manipulative work, India	Increased atmospheric temperatures are associated with increased oxygen uptake, core and skin temperatures and feelings of heat discomfort
Niemelä, Hannula, Rautio, Reijula, and Railio (2002)	Effect of heat stress on daily productivity of Indian call centre workers	Above 72°F (22°C) each additional °C is associated with a 1.8% reduction in labour productivity
Park (2016)	Impacts of temperature shocks on country-level output (measured through payroll) across the United States of America, 1986–2012	Hot days have adverse effects on production: for the average county, an additional day above 90°F (32°C) results in a −0.048% decline in payroll per capita that year
Sahu, Sett, and Kjellstrom (2013)	Impact of heat exposure on cardiovascular stress and work productivity in rice harvesters in India	Hourly productivity decreases significantly once temperature exceeds a threshold, by 5% per degree over 26°C WBGT
Seppänen, Fisk, and Lei (2006)	Review of previous literature on task performance in office environments	Task productivity improves up to a temperature threshold around 20°C to 25°C, then declines significantly; average productivity loss around 2% per °C
Sudarshan, Somanathan, Somanathan, and Tewari (2015)	Impact of temperature on manufacturing productivity and labour supply in India	Indian manufacturing worker efficiency declines substantially on hot days, by c. 2.8% per °C, an effect that is driven primarily by on-the-job task productivity decline as opposed to missed days of work (absenteeism)
Wyndham (1969)	Experimental evidence on the effect of air temperature and wind speed on labour productivity, South Africa	Above a 'wet bulb temperature' of 27°C, there is an exponential decline in performance for manual labour tasks

Source: Authors, based on Hallegatte et al. (2016), Kjellstrom et al. (2016) and Heal and Park (2016).

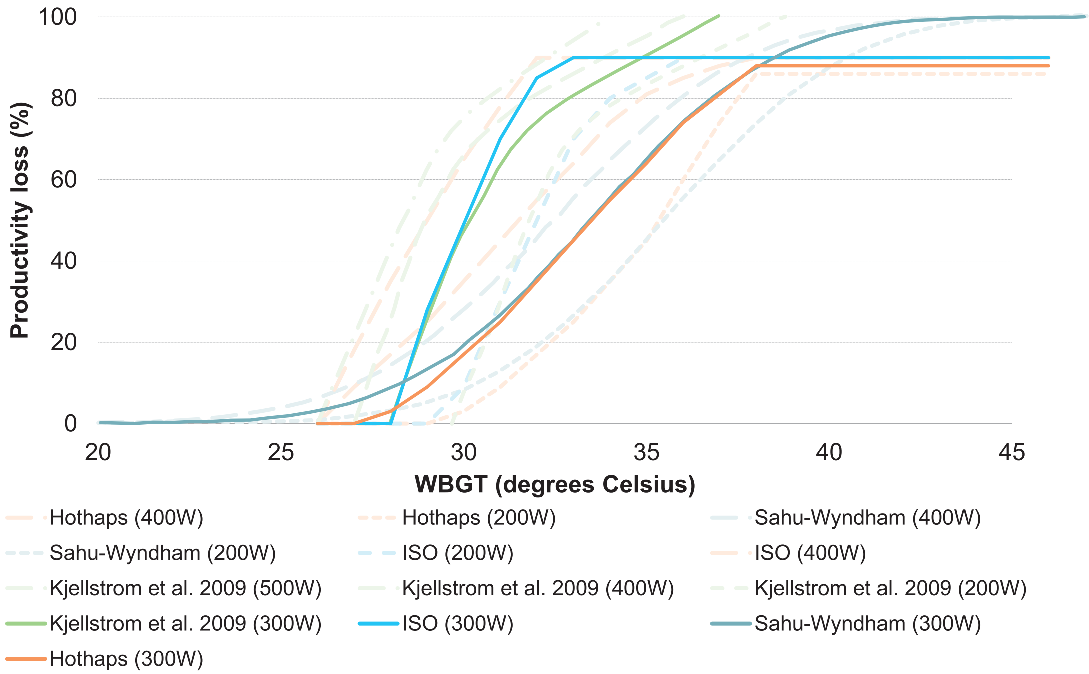

Figure 1. The biophysical link between heat and labour productivity loss. Source: Authors, based on studies cited.

Note: Solid lines represent the central estimates of the relationship for moderate intensity work (300 W) from different sources. Small dashed lines represent estimates from the same source for low intensity work (200 W), long dashed lines represent estimates from the same sources for high intensity work (400 W or 500 W).

overnight temperatures which may affect biophysical recovery capacity outside work hours. It is also important to note that very high heat stress levels can lead to serious health impacts beyond impaired productivity, including heat stroke and other heat-related health symptoms, or even death, especially for people already suffering from cardiovascular, cerebrovascular, respiratory or other chronic conditions (Haines, Kovats, Campbell-Lendrum, & Corvalán, 2006; Sherwood & Huber, 2010). This is captured to a degree in the response functions reaching complete or near-complete productivity loss in Figure 1, but there may be discontinuous impacts as a result of heat stress induced health impacts that are not captured in the continuous functions represented here. These discontinuous impacts underscore that a comprehensive adaptation response to heat stress must include actions to avoid breaching such critical points in addition to attempting to shift workers back down the response function.

The results of empirical studies can be used as an input into economy-wide models that translate the relationship between heat and the productivity of individual workers into estimates of labour productivity effects at larger economic scales. A number of studies explore this question at the national, regional and global scale and for specific contexts, such as cities. An overview of key modelling evidence is presented in Table 2. While different modelling exercises identify different outcomes depending on the scale, assumptions and time frame, all suggest that heat stress is already a significant economic cost to society. The models also suggest that this is likely to increase over this century, and that the costs are likely to be particularly severe in poorer or developing regions, which tend to have higher baseline temperatures.

Within countries or regions, impacts may also be more keenly felt by poorer populations, due to the incidence of such impacts on sectors with a high proportion of subsistence or low-wage workers, notably labour-intensive and outdoor work such as agriculture, and limited financial adaptive capacity of poorer groups (Hallegatte et al., 2016). Adaptation measures may be less financially viable for lower-productivity occupations, where the avoided productivity loss from a given measure is lower. As a result, those options may only be implemented for higher-productivity – and typically higher-wage – occupations, further entrenching inequalities. For example, Sudarshan et al. (2015) uncover evidence of the selective application of air conditioning technologies for professions with higher value addition.

Table 2. Simulation studies on the economy-wide effect of heat-related labour productivity loss.

Study	Context	Findings
Kjellstrom, Lemke, Otto, Hyatt, and Dear (2014)	Models impact of heat on labour productivity by region in 1975, 2030 and 2050 for sectors with different work intensity: agriculture (high), industry (moderate), services (light)	Climate change will reduce available working hours in all regions, with a capacity loss of up to **5% loss by 2050 in affected areas**. The largest impacts are in Sub-Saharan Africa, South Asia, South East Asia and Oceania.
Kopp et al. (2014)	Models the reduction in the proportion of time working during the hottest months in the United States of America to 2099	Under a high climate change scenario, heat increases would lead to **significant productivity losses of up to 3%** across almost all of the USA
Costa, Floater, Hooyberghs, Verbeke, and De Ridder (2016)	Models the impact of heat stress on labour productivity in Antwerp, Bilbao, and London to 2100, including sectoral analysis of expected costs	In a warm future year (2081–2100), **total losses to the urban economy range between 0.4% of GVA for London and 9.5% for Bilbao**. Some sectors are more exposed to economic losses – for example, financial services, public administration and retail trade are most exposed in London
Kovats, Lloyd, Hunt, and Watkiss (2011)	Assesses the potential impacts and economic costs of selected health impacts in Europe due to climate change in 2080, including labour productivity effects	Under one scenario, Southern Europe is estimated to see average productivity losses between 0.4% and 0.9% by 2080. **Total productivity losses for Europe could cost between EUR 300 million and EUR 700 million per year by 2080**, (less under a scenario with increased mitigation efforts)
Roson and Sartori (2016)	Estimates the damages linked to reduced labour productivity for 140 'regions' in the Global Trade Analysis Project database, for a 3°C temperature increase	**A 3°C temperature increase is projected to lead to costs of up to 8% of GDP** in some countries due to impacts on labour productivity, with West African projected to be the worst affected
Dunne, Stouffer, and John (2013)	Assesses loss of labour productivity during the hottest months in each part of the world over the period 1975–2200	Reductions in work capacity, during the hottest months already occur at the global level, on the order of 6% to 10%. **By 2100, the reductions in the hottest month may reach 20% to 37**%, depending on the climate change scenario, though reductions may lower during cool months (1% to 5%). By 2200, reductions in hottest month could reach 61%.
Kjellstrom, Lemke, and Otto (2013)	Estimates losses due to heat stress for the hottest month of the year in South East Asia for different work intensities, comparing 1975 with 2050	**High intensity work in the sun is most affected, with a 29% loss of annual work hours**. Medium intensity work in the sun is projected to face losses of c. 15%, while work in the shade or indoors is expected to see lower losses.
DARA & Climate Vulnerable Forum (2012)	Applies estimates of labour productivity loss with temperature to model costs of heat stress in 2010 and 2030, by country	**The annual global cost of reduced labour productivity due to heat is projected to increase from USD 300 billion in 2010 to USD 2.5 trillion in 2030**. Costs are expected to be particularly high in Sub-Saharan Africa, Central America, South Asia and South East Asia.
Zander, Botzen, Oppermann, Kjellstrom, and Garnett (2015)	Self-reported estimates of absent-eeism and reduced performance caused by heat in Australia during 2013/2014 to estimate economic costs of labour productivity	The annual costs of heat stress on workers are c. USD 650 per person across a representative sample of 1726 employed Australians, suggesting an **annual economic cost for the whole workforce of around USD 6 billion**, equivalent to 0.33% to 0.47% of Australia's GDP
Kjellstrom et al. (2016)	Models global losses (by region) due to climate change-induced temperature increases comparing 1995 with 2085	The most affected regions are projected to see **reductions in total working person-hours of between 1% and 10**. South America, Africa, South Asia, South East Asia and Oceania are projected to be the worst affected regions

Source: Authors and Kjellstrom et al. (2016).

3. Mapping the adaptation solution space

There are a wide range of specific adaptation options that can soften the link between temperature and labour productivity identified in section 2. Based on the feedback of experts (consultants, academics and development professionals) and a review of the available literature (see Vivid Economics, 2017 and the references cited in section 5), we map the universe of potential adaptation measures according to the following four factors:

- *Type of response:* We classify measures as 'technical', 'infrastructural, regulatory and planning', 'behavioural', or 'research and development'. Technical measures are, for example, engineering responses to cool workspaces, such as air conditioning or green roofs (a building roof that is fully or partially covered in soil and vegetation). Regulatory and policy measures are about building standards, 'green' urban design (for example, increasing urban greenspace), or the public promotion of particular technologies. Behavioural responses operate at individual or firm level, and include changing working hours, locations, or employment type. Research and development (R&D) measures refer to pilot programmes and research to improve the effectiveness of adaptation measures or develop new adaptation options.
- *Primary agent of change:* To understand the implications for policy, we consider whether the main driver of uptake of the measure is individuals, the private sector, or government.
- *Feasibility of implementation***:** We consider the likely feasibility of implementing adaptation options at a sufficient scale to significantly reduce labour productivity loss. While technical and economic feasibility will be a question of engineering and cost, in this initial mapping we refer more broadly to potential barriers to wide-scale implementation. For example, while 'assisted migration' away from hot areas could be attractive from the perspective of reducing productivity losses, the social implications of doing this at scale might be considerable, putting in question the practicality of migration as a major adaptation solution.
- *Potential scale of impact:* We consider what the scale of potential impact is for each measure – for example, some measures might be very effective but with a more limited possibility for use as a wide-scale solution.

The results of this classification exercise are summarized in Figure 2, with further detail on individual adaptation options provided in Annex 1. While some of the classifications follow directly from the reviewed literature (e.g. type of response, primary agent of change), others required a more critical assessment of the evidence, which was derived from expert reviews (e.g. estimation of feasibility, potential scale of impact).

The figure suggests a considerable degree of correlation between 'type of response' and 'primary agent of change'. Some responses could arguably fall across typologies – for example urban design options fall partly under policy and partly under technical solutions. For the most part, however, technical responses fall largely on private actors for implementation; regulatory, policy and R&D-focused adaptation is driven primarily by government, and behavioural responses are spearheaded primarily by individuals and firms.

The figure identifies suggestive patterns rather than rigid relationships. For example, while adaptation options are classified according to the primary agent of change, in practice several actors will often be involved in implementing actions. Sometimes there may be more than one 'primary' agent and there are likely to be interactions between different actors and some instruments. Governments may lead public sector investment in and incentivisation of research and development that results in societal benefits (public goods), but private firms also engage in R&D in pursuit of their private business objectives. Private individuals are the primary agents of behavioural adaptation, choosing to take a rest, have a drink or wear appropriate clothing, However, governments are instrumental in creating an environment or regulations that facilitate change in social norms. They may enact work place regulations to encourage shifts in working hours or lead by example in their role as an employer.

4. An assessment framework

On the basis of the above mapping, we identified a smaller set of 17 measures, whose cost-effectiveness and technical potential was analysed in more detail. The 17 options were chosen to ensure a reasonable coverage

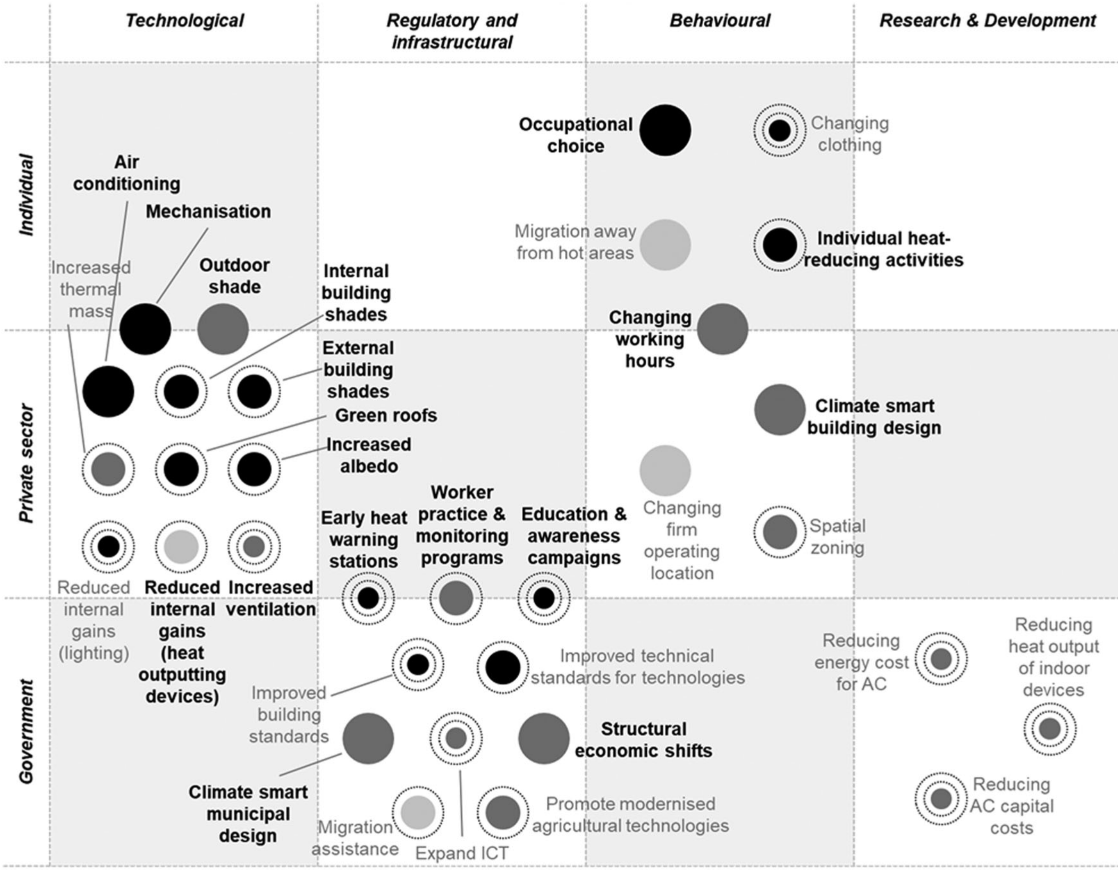

Figure 2. Adaptation options to temperature-related labour productivity loss. Source: Authors.

Note: (1) The size of each bubble indicates the 'potential scale of impact' assessment – larger bubbles indicate larger impact. (2) The shading of each bubble indicates the 'feasibility of implementing the measure' assessment – light shading indicates low feasibility, medium shading indicates medium feasibility, dark shading indicates high feasibility. (3) Bold typeface indicates measures included in the shortlist for this analysis.

of measures across type and primary agent of change but also based on existing evidence about their feasibility and potential impact. (However, no R&D solutions are included, given their long-term and overarching nature).

We use an assessment framework that consists of two parts. The first part evaluates qualitatively the main economic, environmental and social impacts (costs and benefits) associated with each adaptation option. The second part identifies various contextual factors, on which these costs and benefits depend, and assesses the suitability of different options under these different contexts.

The first part of the assessment covers both direct and indirect costs and benefits. The economic costs of each adaptation measure include direct financial costs of implementing the measure, and a range of 'indirect' costs. The direct financial costs include any capital investments that may be required – that is, any one-off up-front cost – and the variable costs associated with maintaining and using equipment. The direct economic benefits are the direct impact of avoided productivity losses, considered in terms of the expected reduction in temperature enjoyed by workers under each option.

The indirect costs and co-benefits we consider include environmental, health and socio-economic impacts. For both indirect costs and co-benefits we consider: knock-on effects on climate change mitigation through greenhouse gas emissions; interaction with other types of climate change impacts and policies; impacts on the natural environment, such as biodiversity and water quality; socioeconomic impacts, in particular job creation, education, leisure and amenities, and health impacts through, for example, pollution accidents, and other biophysical responses to increased temperatures.

The magnitude and relative importance of these costs and benefits are highly dependent on context. The relative merits of an adaptation option cannot be considered in isolation from the context in which the measure would be implemented. A particular measure might be expected to be effective at reducing heat stress on workers – and therefore mitigating productivity losses – in 'average' conditions, but might be much less effective in a specific setting. An accurate 'generic appraisal' producing robust, generally applicable cost–benefit ratios is therefore not possible.

In acknowledgement of this statement, the second part of the assessment gauges the suitability of adaptation options to different contexts. This provides indicative evidence on the circumstances under which different measures are more likely to be cost-effective. Key factors that will influence the interaction of costs and benefits in different regions and contexts include:

- *Indoor vs. outdoor:* While some measures to address high temperature impacts on labour productivity are applicable across all workers in an economy, across all sectors and work environments, others are specific to certain types of environments, or are more effective in certain environments. For example, shifted working hours can be applied across all sectors, but might be particularly effective for outdoor workers that are exposed to intense direct sunlight during the hottest period of the day. Some technical measures like air conditioning, increased ventilation or window shades would only be applicable to indoor workers.
- *Urban vs. rural:* Reducing heat stress on workers will be very different in a densely populated urban setting compared to a dispersed rural environment. In major urban centres, there will also be a '*heat island'* effect, which may raise temperatures further, particularly in the evenings. In rural settings, the electricity grid and generation infrastructure may be weaker, and the workforce predominantly outdoors, which will imply a different set of solutions than would be appropriate in major urban centres.
- *Temperature profiles – base and peak:* While some measures will reduce indoor temperatures all the time, others may be most effective in dealing with temperature volatility. The most cost-effective solution mix will be different in a setting of high, but low volatility, temperature, compared to one of lower average, but higher volatility, temperature.
- *Energy costs and carbon intensity of energy:* To the extent that adaptation measures require electricity, the cost of electricity – and the associated carbon emissions – impact on their cost-effectiveness, and thus the appropriateness of measures to different contexts. For example, air conditioning as an adaptation measure will be less appropriate in situations where the electricity system is already strained, and where increased usage could affect the quality of service, resulting in more blackouts. Conversely, air conditioning will be a more attractive solution in the presence of abundant low-carbon solutions, such as large-scale hydropower or cost-effective solar PV.

A key challenge for long-lived adaptation solutions is uncertainty about the future climate. While the basic geophysical relationships between greenhouse gas emissions, radiative forcing and global mean temperature are increasingly well understood, the detailed implications for local climate conditions, and how they may unfold over time, are not. This creates a unique challenge to decision makers, who must adjust to a climate regime that changes continuously in ways that are largely unknown. Various decision-making heuristics and tools have been put forward to enable adaptation decisions under these circumstances (see Watkiss & Hunt, 2016 for an overview). They put a premium on adaptation options with the following properties (Fankhauser, 2017; Fankhauser, Smith, & Tol, 1999):

- *'No' or 'low' regrets:* Measures that deliver a net positive socio-economic value in all (or most) future states of the world can be described as '*low-regrets*' measures. Whatever happens in the future, no-regrets investments will turn out to be worthwhile, usually because they entail benefits that are not contingent on particular climate change scenarios.
- *Flexibility:* Some adaptation strategies may have the ability to adjust and evolve, as information regarding uncertainties is revealed over time. For example, 'modular' options may be scaled up over time, while other investments may create flexibility by improving understanding of uncertainties over time (i.e. the value of pilot schemes and of R&D).

Both 'no' and 'low-regrets' and flexible adaptation solutions allow investments to go ahead without the need to 'wait and see' or the risk of locking in irreversibly an undesirable response type. We therefore assess the different adaptation options against these characteristics.

5. Insights on specific options

Our evaluation of the 17 adaptation options considered is summarized in Table 3. For each shortlisted option we undertook a qualitative assessment, based on the available literature, expert opinions and stakeholder dialogues, of the relative merits and challenges for implementation using the assessment criteria outlined above. This assessment was used to create a scaled relative appraisal of each adaptation measure along several dimensions that allows for comparison across measures.

It bears repeating that the findings in Table 3 are only indicative. The concrete adaptation solutions that are best suited for a specific socio-economic and environmental context will have to be identified through detailed technical studies. Nevertheless, a rough assessment of the applicability of different options is helpful in identifying the adaptation measures that are most likely to be cost-effective in a particular context. This will allow decision makers to find the sub-sets of measures that are relevant to the contexts they are working in, and identify the most suitable options from within this subset by considering whether and how the individual contextual factors apply to the situation under consideration.

The left panel of Table 3 summarizes the relative importance of various direct and indirect costs and benefits for each option. It sets out the relative importance of each cost and benefit component in the form of a heat map: the stronger the shade of grey, the greater these expected costs and benefits are likely to be under most circumstances. However, the exact cost of achieving a given unit of benefit, such as an 'effective work hour' productivity increase, will be context specific.

The relative importance of uncertainty and contextual factors is summarized in the right panel of the table. The shading indicates how a measure performs in a particular context, according to expert judgement.[2] The darker the shade of grey, the better suited a measure is for the contextual factor in terms of potential to reduce temperatures.

While the balance of costs and benefits will be heavily dependent on local markets and contexts, some generic lessons emerge. As in Table 3, we group them by response type, that is, insights about technical solutions, planning / regulatory interventions and behavioural solutions.

5.1. Technical solutions

Among the technical solutions, air conditioning unsurprisingly stands out as a very effective way to reduce temperatures for indoor workers. With the appropriate technology, air conditioning can both reduce high base temperatures and respond flexibly to high peak temperatures. The ability to respond quickly to variation in temperatures differentiates air conditioning from many of the other options.

However, air conditioning performs less well where the (incremental) cost of electricity generation is high, where the carbon intensity of electricity production is high, where access to electricity is low and in situations where the power grid is already under strain, and where additional power demand would increase the risk of blackouts. Furthermore, while air conditioning reduces the internal temperature of buildings, it increases temperatures outside buildings, which can contribute to the urban heat island effect and to heat stress to people outside. This is likely to have most effect in densely populated areas where the heat island effect is most pronounced. Absent policy intervention to correct these externalities, the extent of penetration and usage of air conditioning may therefore not be optimal. Air conditioning may be over-used.

Alternatives to air conditioning may have a more limited range of impact, but can be as effective in the appropriate circumstances (e.g. within a particular temperature range, or if combined with incentives for behavioural responses). Many of them have a more attractive profile of co-benefits and indirect costs than air conditioning. Shading options and other passive design options, such as increased ventilation and roof albedo, will therefore often be attractive (e.g. Lundgren & Kjellstrom, 2013).

Table 3. Appraisal of adaptation options.

#	Adaptation response	Direct benefits	Co-benefits				Direct costs		Indirect costs				Uncertainty		Contextual factors							
		Reduced productivity loss	Climate	Socio-economic	Environmental	Health	Fixed costs	Variable costs	Climate	Socio-conomic	Environmental	Health	Low-regrets	Flexibility	Indoor	Outdoor	Urban	Rural	High base temperature	High peak temperature	High energy costs	Carbon-intensive energy
Technical adaptation measures																						
1	Air conditioning																					
2	Increased ventilation																					
3	External shading																					
4	Internal shading																					
5	Reduced internal gains																					
6	Increased albedo																					
7	Green roofs																					
8	Mechanisation																					
9	Outdoor shade																					
Infrastructural, planning and regulatory adaptation measures																						
10	Climate smart municipal design																					
11	Structural economic shifts																					
12	Early heat warning stations																					
13	Education and awareness campaigns																					
14	Worker practice & monitoring programs																					
Behavioural adaptation measures																						
15	Occupational choice																					
16	Changing working hours																					
17	Individual heat-reducting activities																					

strong benefit/cost | strong cost | strong in context | weak in context

Note: Costs and benefits are ranked on a four-point scale: none (blank), low (light shading), moderate (medium shading), high (dark shading). Contextual factors are ranked on a four-point scale: weak in context (hatched shading), neutral in context (blank), good in context (medium shading), strong in context (dark shading).
Source: Authors, based on the cited literature.

Green roofs, while less effective at reducing temperatures in all contexts, bring potentially large co-benefits in terms of improving the quality of the built environment, reducing health problems associated with particulate matter, and reducing noise pollution (Susca, Gaffin, & Dell'Osso, 2011; Virk et al., 2015). They are most appropriate in densely populated settings, where they can potentially reduce the urban heat island effect. Green, and in particular, 'cool' roofs have a higher albedo (reflectivity) than traditional 'grey' roofs, meaning they absorb less solar energy from the sun's rays, with two effects: (i) less heat is transferred into the building, and (ii) the air around a green or cool roof remains cooler, reducing the urban heat island effect (Banting, Doshi, Li, & Missious, 2005; Claus & Rousseau, 2012; Foster, Lowe, & Winkelman, 2011; Rosenzweig, Gaffin, & Parshall, 2006).

5.2. Infrastructure, planning and regulatory interventions

Among planning and regulatory interventions, climate-smart municipal design stands out as perhaps the most important strategic intervention. This is particularly the case in rapidly growing cities, where city planners must get the basic structures right to ensure low-carbon, climate–resilient urban development (NCE, 2014). Concern about urban labour productivity is only one of many aspects they need to consider, and there are synergies with other urban development objectives, for example with respect to health and wellbeing. It is in these long-term, strategic decisions – where urban landscapes are locked in for many decades – that a solid understanding of climate uncertainties and the need for flexible, low-regrets solutions is pertinent.

Structural economic change is a contextual factor as much as an adaptation measure to alleviate heat-related labour productivity loss (Kocornik-Mina & Fankhauser, 2015; Vivid Economics, 2015). On the one hand, economic transformations are rarely driven by climate. No countries have initiated economic shifts as an explicit means of adapting to climate change. On the other hand, the on-going shift from farm employment to industrial and service jobs, observed in many countries, is as powerful a determinant of heat-related productivity loss as many deliberate adaptation measures. Shifting economic activity from sectors most exposed to high temperatures – either because they are outdoor or high-intensity – to sectors with low exposure can significantly reduce the impact of heat on worker productivity. Shifting employment from agriculture to manufacturing, industry and services reduces both the number of workers exposed to high temperatures, and the impact of those temperatures on subsequent economic output.

However, economic shifts also change the context in which further adaptation measures are undertaken. Structural change alters the need for, and the potential benefit from, other adaptation measures such as shifting working hours, air conditioning and green roofs. It is in this sense that structural economic change is also an important contextual factor.

5.3. Behavioural solutions

Among behavioural solutions, shifting working patterns stands out. Shifting working away from the hottest parts of the day (while maintaining the total number of hours worked) could be particularly effective in sectors where high-intensity, outdoor working is common. While varied working patterns are common, the barriers to large-scale shifts in working hours will often be cultural and the associated costs therefore intangible. However, there are also known health effects to shifting work patterns (Harrington, 2001).

There are various examples of working hours which vary by time of day or by season. While not all of these were implemented specifically to mitigate the impact of high temperatures on labour productivity, they do inform how a successful working-hours policy could be implemented. For example, traditional Spanish working hours include a long pause during the hottest part of the day to protect workers from the midday heat. Japan and Norway promote seasonal shifts in working hours to increase leisure and family time in the long summer evenings (Government of Norway, 2017; The Japan Times, 2016). India's National Disaster Management Authority has advised workers to schedule high intensity activities for cooler periods of the day, and to avoid working outside during peaks hours of 12.00 PM to 3.00 PM (Government of India, 2016).

The social and economic costs associated with behavioural responses such as changing work hours are not well understood and should not be underestimated. Promotion of flexible working hours may be easier to achieve in some places than in others. In Norway, income levels are high and the trade-off between working hours and income may facilitate a degree of flexibility between summer and winter working. On the other hand, in India working hours are longer, especially among low-income working groups. Changing business hours to cooler seasons of the year, or even within a given day, while 'efficient' may result in a reduction in overall working hours and associated income. While heat exposure can have important implications on poverty – and indeed is likely to affect lower income workers most (especially high-intensity, outdoor agricultural workers) – it is important to also consider the costs of adaptation from a distributional perspective.

Other behavioural options, such as regular drinks breaks and cool showers on-site (Jackson & Rosenberg, 2010) – but also measures such as spatial zoning, heat warning systems, outdoor shades and individual heat cooling measures that fall into the technical or regulatory categories – have relatively narrow benefits. However, they are also relatively low cost and with sufficient worker education (Riley, Delp, Cornelio, & Jacobs, 2012) could therefore be highly effective complements to more wide-ranging, but also more capital-intensive interventions.

6. Conclusions

Progress on poverty alleviation, a key sustainable development goal, is impossible without a sustained increase in labour productivity. The pursuit of labour productivity is, therefore, central to development policy. Any external shock, such as climate change, which negatively affects the productivity of workers, is a potential concern. This is particularly the case in poorer countries, which are more susceptible to heat-related productivity shocks.

Our knowledge is incomplete about the economy-wide effects of higher temperatures on the productivity of modern, diversified economies, where output is produced in contexts ranging from outdoor agriculture to office work in air-conditioned buildings. However, the biophysical impact of higher temperatures on worker performance is well-documented. The available evidence suggests that heat-related productivity loss, already today, could be on a par with health-related barriers to labour productivity. Heat-related productivity loss is also one of the most prominent 'market impacts' in studies on the economic effects of climate change, although these studies are characterized by high uncertainties.

Fortunately, there is a range of adaptation options and many of them appear cost-effective. Working conditions are to a large extent a matter of individual or societal choice, which means that heat-related labour productivity loss can potentially be alleviated through adjustments in these conditions. The solution space can be structured according to response type (technical, regulatory/infrastructural, behavioural or R&D), and the responsible agent (individuals, business, government), with feasibility and scale of impact among other important characteristics.

While the importance of local contexts prevents a general ranking of adaptation measures, there are rules of thumb as to when particular solutions are likely to provide value for money.

Some measures, such as passive cooling mechanisms, are likely to be 'low regrets' in many contexts. They are worth considering independently of any climate change concerns.

In general, behavioural measures such as changing working hours to avoid the hottest parts of the day/year, and passive adaptation options such as regular drinks breaks, are likely to be effective and often cheaper than technical solutions in dealing with high peak temperatures, especially where these are most keenly felt by high-intensity outdoor workers. In countries like India, the amount of work hours lost due to excessive heat is concentrated in a couple of months of the year, with other months experiencing few heat-related losses (Vivid Economics, 2017). There may be institutional and practical constraints on the extent to which working hours may be moved to the cooler winter months, or to cooler parts of the day in summer months, but behaviour shifts like this have appeal. Proactive strategic interventions, such as climate-smart municipal design, are important complements for more reactive measures. Adjustments to building design are most suitable to respond to high base temperature, while air conditioning can respond flexibly to short temperature peaks. However, the merit of energy intensive solutions like air conditioning depends on the cost, carbon content and accessibility of energy.

Adaptation decision-making is complex. There are no general solutions. The ultimate choice of options will require careful evaluation to ensure value for money. The economic merit of most options will be heavily context-specific and depend on such factors as cultural norms, population density, the physical environment and the availability of resources. The effects of adaptation on poverty alleviation will depend not just on whether the overall benefits are enough to offset the costs, but also on the distributional impacts of each measure. On a sector by sector basis, it is possible that for the most productive sectors, with already higher wages, the gains in productivity may be enough to offset the costs of adaptation by individuals or businesses, but that in sectors associated with lower per capita gains, government-led adaptation may be necessary on equity grounds.

While it is helpful to understand the landscape of adaptation options – and reassuring to know that many of them may be highly cost-effective – there is no substitute for the careful technical, economic, social and environmental appraisal of all concrete proposals.

Notes

1. The impact of ill-health on *individual* productivity can be much higher than heat-related productivity effects. However, since fewer individuals are affected, the *aggregate* effect on labour productivity across the population is lower.
2. Expert judgements were guided by the level of early benefits (to judge the low-regrets potential) and the likely economic life of an investment (to judge flexibility).

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Annex 1: An Overview of Adaptation Options.

Adaptation response	Type	Actor	Feasibility L / M / H	Impact potential L / M / H	How this response operates
Air conditioning	Technical	firm	H	H	Increased use of installed air conditioning units decreases inside temperatures in work spaces that already have air conditioning installed Increased prevalence of air conditioning units to expand the number of work places that are able to reduce internal temperatures
Increased thermal mass (heat absorption)	Technical	firm	M	M	Increased ability of buildings to absorb and store heat energy, so that internal building temperatures increase more slowly over time, reducing internal temperatures
Increased ventilation	Technical	firm	M	L	Increased ventilation (natural or mechanical) can reduce heat through increasing flow of cool air through buildings.
External building shade	Technical	firm	H	M	Increased shade reduces direct solar radiation entering buildings, reducing internal temperatures.
Internal building shade	Technical	firm	H	M	Increased internal shade (for example, curtains or window film) shade reduces direct solar radiation inside buildings, reducing internal temperatures.
Reduced internal gains: reduced lighting	Technical	firm	H	L	Reduced lighting eliminates internal source of heat in buildings.
Reduced internal gains: reduced use of heat-outputting devices (e.g. electronics, ovens, furnaces)	Technical	firm	L	M	Reduced use of heat-outputting devices eliminates internal source of heat in buildings, including reduced use of heat-outputting devices (e.g. electronics, ovens, furnaces)
Increased roof (/wall) albedo	Technical	firm	H	M	Increased roof albedo leads to increased reflection of solar radiation for buildings, reducing solar heat gains
Green roofs	Technical	firm	H	M	Green roofs are roofs that are partially or completely covered with vegetation. Green roofs can improve the thermal performance of roofs, reduce cooling loads on buildings, and reduce average temperatures in the vicinity of the roof by reducing re-emission of solar radiation as heat.
Mechanization (reduce work effort level)	Technical	firm / ind	H	H	Increased use of mechanization in labour-intensive activities to reduce level of effort required by workers, thereby reducing heat stress.
Outdoor shade	Technical	firm / ind	M	H	External shade reduces direct solar radiation felt by outdoor workers, including both artificial structures and natural shade (trees, plants).
Improved technical standards for buildings	Regulatory & infrastructural	govt	H	L	Building-level design and regulatory standards that lead to reduced internal temperatures, through overall building design including, for example, green roofs.
Improved technical standards for climate-appropriate technologies (e.g. ventilation, insulation, building materials)	Regulatory & infrastructural	govt	H	M	Technical standards for specific technologies or their use to reduce internal temperatures in buildings (for example, natural ventilation, materials for increased thermal mass, use of insulation to avoid increased internal heat gains).
Climate smart design (zoning, municipal planning, etc)	Regulatory & infrastructural	govt	M	H	City-, zone-, region- or country-level requirements for urban or rural planning to reduce temperatures inside and outside buildings. For example, urban

(*Continued*)

Continued.

Adaptation response	Type	Actor	Feasibility L / M / H	Impact potential L / M / H	How this response operates
					planning though increases in vegetation, green surface areas, water bodies and urban ventilation pathways could reduce any urban heat island effect.
Advance economic structural shifts towards industries involving non-outdoor work, less energy-intensive work	Regulatory & infrastructural	govt	M	H	Decrease of activity in sectors exposed to high outdoor temperatures (and increase of activity in sectors where work occurs indoors in lower temperatures) reduces exposure of workers to high temperature conditions.
Expanding the use of information and communications technologies	Regulatory & infrastructural	govt	M	L	Expanded use of ICT would lead to decreased work-intensity of jobs, and facilitate a shift towards indoor and/or less energy-intensive work.
Promote modernized agricultural technologies	Regulatory & infrastructural	govt	M	M	Policies that enable a shift towards increased mechanization of agricultural activities, or increased capital-to-labour ratios in the agriculture sector.
Migration assistance	Regulatory & infrastructural	govt	L	M	This response aims to assist the individual- or firm-level response of moving from areas with high temperatures to areas of low temperatures (discussed below).
Early heat warning stations	Regulatory & infrastructural	govt / firm	H	M	Early warning stations would raise awareness of high temperatures among workers, enabling them to adjust their working hours, or reduce their labour supply or intensity to avoid negative impacts on health.
Education and awareness campaigns (on risk of heat)	Regulatory & infrastructural	govt / firm	H	L	These measures would increase general awareness of risks that working in high temperatures pose to human health, encouraging workers to reduce their labour supply or intensity to avoid negative impacts on health, and training individuals on how to use cooling measures (such as building cooling systems, reducing sources of internal heat gains).
Worker practice and monitoring programmes (e.g. rest, scheduling and acclimatization regimes, bio-physical monitoring and other related measures)	Regulatory & infrastructural	govt / firm	M	L	These business-level measures would enable monitoring of workers activities and encourage activities to reduce the impact of high temperatures on human health. Programmes that encourage acclimatization could reduce levels of heat stress associated with a given temperature level.
Occupational choice	Behavioural	ind	H	H	Individuals may choose to switch between occupations to reduce their exposure to high temperature working conditions.
Changing working hours	Behavioural	firm / ind	M	H	Individuals or groups alter the hours they work to better cope with high temperatures. This could include changing working hours within the working day to working during cooler periods in the day, or distributing working hours across additional days (i.e. days that were previously non-working days) to reduce the hours worked in high temperature conditions on a given day.
Changed choice of clothing	Behavioural	ind	H	L	Heavy clothing can increase the effective intensity of work tasks. Changing clothing to lighter choices can therefore reduce the effective intensity of work in different sectors, and thus reduce the impact of temperatures on productivity loss.
Individual heat-reducing activities	Behavioural	ind	H	M	Individuals can take actions to reduce their body temperatures, such as consuming cold beverages, taking cooling shower breaks, using individual cooling devices (fans).
Migration (away from hot areas)	Behavioural	ind	L	H	Individuals may relocate away from areas of higher temperatures to areas of lower temperatures to reduce the productivity loss due to higher temperatures.
Change firm location / relocate facilities	Behavioural	firm	L	H	Businesses may relocate operating locations from areas of higher temperature to areas of lower temperature to reduce the labour productivity loss due.

Spatial zoning	Behavioural	firm	M	M	This measure involves using different areas within buildings to avoid parts of buildings that receive direct solar radiation during the day. This could be complemented by the provision of cooling areas (such as 'cool rooms') to enable workers to cool down for a short period during the working day (avoiding full workspace cooling).
R&D in reducing adaptation flow cost (energy cost) for air conditioning	R&D	govt	M	L	Investments in understanding how to reduce the energy cost of using air conditioning, to enable greater flow use of this adaptation measure.
R&D in reducing adaptation stock cost (AC units) for air conditioning	R&D	govt	M	L	Investments in understanding how to reduce the installation cost of air conditioning, to enable greater stocks of (and ultimately greater flow use of) this adaptation measure.
R&D in reducing heat output of indoor devices (e.g. electronics, ovens, furnaces)	R&D	govt	M	L	Investments in understanding how to reduce the heat output from indoor devices, to enable greater reductions of internal sources of heat.

Source: Authors.