THREE ESSAYS ASSESSING THE ECONOMIC IMPLICATIONS OF HEAT STRESS IN LABOR

by

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ABSTRACT

This dissertation assesses three aspects of the economic implications of heat stress-related labor-capacity losses. Given that low-income countries around the tropics are at most risk, our analyses focus on these and the vulnerable households within them. First, we consider the optimal allocation of labor for small-scale agricultural households. We build an agricultural household that takes into consideration that these households will be affected by heat stress as producers, consumers, and workers simultaneously. Using this model and a sample of households from Pakistan, we determine that for most households it would be optimal to increase their supply of family labor to agricultural self-employment. However, if work preferences are also affected, even modestly, then decreased supply of family labor to agriculture would be observed.

Next, we turn to country-level welfare losses across the globe focusing on the role of trade in mitigating or exacerbating these. We consider nine West African economies and determine which benefit from international trade, which are made worse-off, and we fully delineate the factors and channels that determine this. Broadly, we find that net exporters of agricultural commodities will benefit via global price changes, and conversely net importers will be made worse off by global price changes. However, countries that experience especially large labor capacity losses in their export sectors can also see loss-mitigating effects from trade as their export prices rise more sharply that the global average. An alternative perspective shows that some countries are affected more by their own heat stress-related productivity losses, while others are affected more due to global changes.

Lastly, we consider the poverty impacts of heat stress-induced labor capacity losses in West Africa. Using a macro model, we determine changes in real incomes of households near poverty in seven West African countries, then use household microsimulations to determine poverty impacts. We find that poverty impacts are heterogenous in direction and magnitude across household-types and countries. In five of the seven countries, poverty headcounts increase, ranging from 1.5% in Cote d'Ivoire to 7.8% in Nigeria. In two countries, there is either little change or a decrease in poverty: in Cameroon poverty increases by 0.6% and in Guinea it decreases by 1.7%. The key channel behind this heterogeneity is how loss of labor productivity affects relative returns to factors of production. Returns to unskilled agricultural labor can increase due to increased demand for this labor to dampen losses of agricultural output.

CHAPTER 1. INTRODUCTION

This dissertation addresses three aspects of the economic implications of increasing heat stress in human labor. As the climate becomes warmer, the ability of humans to perform outdoor, manual labor will be affected (Dunne et. al. 2013, Kjellstrom et. al. 2009; Kjellstrom et. al. 2016; Kjellstrom et. al. 2018; Bröde et. al., 2018). We know that in addition to increased health risks, mortality, and costs to the well-being of workers, there will be widespread economic consequences that reverberate through-out the global economy (Orlov et. al. 2020; de Lima et. al., 2021). The loss of capacity/productivity of a factor of production that is critical to sectors such as agriculture and mining particularly in low-income economies will induce a wide array of market responses. While high-income economies could potentially adapt with new technologies, this cannot be assumed for low-income economies and households whose low levels of wealth tend to prevent technology adoption. It is these economies, and the households close to poverty within them, that are the focus of the analyses undertaken here.

In Chapter 1, we ask how increased heat stress will affect the labor allocation decisions of agricultural households in low-income economies. The regions of the world that are projected to suffer the most heat stress intensification and the largest labor capacity losses are regions that are home to large populations of low-income, small-scale agrarian households. A priori, it is not obvious how these households will respond. There are potentially several margins of adaption, but we focus on the simplest, lowest cost adaptation: altering the allocation of labor between agricultural and non-agricultural uses. When heat stress leads to loss of labor productivity in agriculture, would such households intensify their labor allocation in agricultural production further, to prevent loss of production and income? Or would they choose instead to re-allocate labor to non-agricultural uses, allowing agricultural production to fall and earning their livelihood elsewhere? In other words, what is the likely sign of the relationship between family labor supplied to agriculture and heat stress?

Chapter 1 addresses these questions by building a microeconomic model of agricultural households' decision-making. We use this to determine these households' theoretically optimal labor allocation under heat stress. We find that the direction of change in labor supplied to agriculture due to heat-stress-induced labor productivity loss in agriculture is theoretically ambiguous. It depends on the elasticity of substitution between labor and non-labor inputs and the intensity of labor use in the base. All else equal, we find that if this elasticity is low and the initial share of labor is also low, the likelihood of an intensification of labor in agriculture being optimal in response to heat stress is maximized. This result is intuitive: if it is difficult to substitute labor with capital (or other non-labor inputs) in agriculture and furthermore, labor use in agriculture is initially low, then allocating more labor to agriculture is optimal. However, this result is subject to caveats. One major caveat is that it is based only on profit or production-side considerations. If, however, it is the case that households have preferences over agricultural and non-agricultural work, and that a loss of productivity coincides with increased unpleasantness of (or disutility from) agricultural labor, households may decrease their labor allocation to agriculture despite profit incentives that push for the contrary. Using data from a sample of agricultural households in Pakistan to parameterize our model, we find that it would be optimal for most households to increase their family labor supplied to agriculture. However, we also find that fairly modest preference changes would be sufficient to overturn this result and cause instead a decline in family labor allocated to agriculture. We find this to be true under both high and low values of the elasticity of substitution in agriculture as well as alternative assumptions about labor market conditions. Another caveat is that our findings assume “all else equal” i.e., price and wage changes that would result from aggregate and general equilibrium effects are not accounted for. Chapters 2 and 3 consider general equilibrium effects.

Chapter 2 turns to a global, macroeconomic view of the economic implications of heat stress-related labor productivity losses with a focus on the role of trade. As opposed to Chapter 1, where we consider micro-level responses and only one segment of the economy, here we account for the fact that labor across all sectors and all regions of the global economy will be impacted simultaneously, but heterogeneously. Countries that are already hot and humid will be impacted disproportionately as will sectors that are intensive in the use of manual labor that entails outdoor exposure. This will induce re-allocations of factors of production, and heterogenous changes in production levels, commodity prices, and factor returns across sectors and regions. Given these heterogenous impacts, international trade has the potential to mitigate or exacerbate regional economic welfare impacts. The effects of international trade will be driven by multiple channels. On the one hand, any individual country will be affected due to its own labor and domestic economy being affected by heat stress. On the other hand, countries that are open to international trade will also be affected by global economic shifts since all other countries including their trade partners are also affected. The objective of this chapter is to provide a complete decomposition of the role of trade and its drivers. We address the questions: which countries will see positive trade effects, and due to which channel? What features of these economies determine these outcomes, (given what we know about the dispersion of heat stress productivity losses across sectors and regions)?

As mentioned, we use a global general equilibrium model, GTAP, for this analysis. Within this model we simulate new, more precise estimates of labor capacity losses defined over 137 regions and 65 sectors and determine the global welfare and terms-of-trade changes that these induce. Next, for a sample of nine West African economies, we use decomposition methods to determine the drivers of these outcomes. More specifically, regional welfare losses are decomposed to determine the portion that can be attributed to terms-of-trade (ToT) effects. In turn, regional ToT changes are decomposed, and this is done in two complementary ways. The first decomposition determines the extent to which ToT changes are driven by global price changes, and the extent to which these are driven by region-specific price changes. The second determines, more explicitly, the extent to which regional ToT changes are driven by a country's own heat stress (-related productivity changes) and the extent to which these are driven by global heat stress (-related productivity changes). In our sample of countries, Cote d'Ivoire serves as one illustrative example. It experiences the largest ToT improvement. Our first decomposition reveals this is because, as a net exporter of agricultural commodities, it is the beneficiary of global increases in agricultural prices, but also that its own export prices rising more than the global average. Our second decomposition reaffirms that its ToT improvement is driven more by heat stress impacts outside of its borders than its own heat stress. Other countries experience ToT deteriorations driven by either falling prices of its own exports, or global increases in the prices of their imports. We find a number of cases within West Africa where heat stress in the rest of the world plays a larger role than these countries' own heat stress.

Finally, Chapter 3 considers the poverty impacts of heat stress-induced labor capacity losses. We know that these labor capacity losses will cause losses of regional production and GDP across the globe. Past studies that have estimated these impacts find that the largest losses occur in South Asia and Africa (Orlov et. al. 2020; de Lima et. al., 2021). These are regions that are home to significant portions of the world's poorest households, yet the potential impact on poverty rates has not been explicitly addressed. Chapter 3 serves to fill this gap. As in Chapter 2, we use a sample of West African economies to determine the extent to which their poverty levels might be impacted and to fully elaborate the factors that determine this outcome. Our analysis takes into account that low-income households (those close to the poverty line) are heterogenous in how they earn their incomes. For example, low-income households that are agricultural may rely in large part on returns to unskilled agricultural labor, whereas urban households may rely more on wages. These household-types will also vary in their consumption patterns. This means that the real incomes of different household-types within any given country will be differentially impacted by heat stress-induced labor productivity changes. In turn, poverty rates across countries would be differentially impacted depending on the household-types that make up the population around the poverty line.

The analysis in this chapter relies on the same model and simulation analysis as Chapter 2 as its starting point. In this case, the model is used to assess impacts on commodity prices and factor returns. These changes in prices and factor returns, along with our estimates of the productivity loss of different types of labor, are then used to determine changes in the real incomes of different household-types considering their different earnings shares, within our sample of West African countries. Next, given these projected changes in the real incomes of households that are close to the poverty line, we conduct a household microsimulation exercise, for each sampled country, utilizing a recent household survey dataset. We find that of the seven West African countries considered, Nigeria and Ghana see the largest increases in poverty of 9.5% and 8.3%, respectively. Note that Nigeria is one of the most populous countries in the world. We further analyze the case of Nigeria as a case-study to delineate the drivers of poverty due to human heat stress. Our analysis shows that its poverty increase is driven in large part by increased cost of living for the poor (rather than declines in “nominal” factor returns). This in turn is driven by sharp increases in the prices of crops in Nigeria where crops make up a large portion of the spending of households near the poverty line. More generally, across all countries sampled, it is non-agricultural households (rural wage earners, and the urban poor) who are most vulnerable to falling into poverty. Among households that we classify as “agricultural”, poverty rates frequently see little change in our results, and *declines* in poverty are also possible. This is because as labor productivity falls, more of it must be attracted into agriculture from other sectors in order to dampen losses of agricultural production (since demand for agricultural produce is inelastic relative to other sectors). This requires higher wages for agricultural labor, which benefits poor households that earn large portions of their income from this factor.

This thesis contributes to the economic literature addressing heat stress-induced labor capacity losses. It considers three distinct aspects of the subject: how heat stress in humans will affect and induce responses at the household level, how economies will be impacted via international trade, and how heat stress could induce changes in regional poverty rates. Thus, it addresses both micro and macro-economic dimensions in order to build a more comprehensive picture of the likely economic responses to climate-induced human heat stress, and the channels by which these are induced. Our analyses are however limited in scope and some important limitations are noted as follows.

In order to identify the channels by which heat-stress-induced labor productivity losses will affect economic outcomes, the scope of these analyses are necessarily restricted to heat stress in humans. However, we note here that in practice, heat stress will also simultaneously affect plants and animals with implications for yields, output, and the distribution of production across countries. The economic consequences of heat stress in general (which will affect humans, plants, animals simultaneously) will therefore be the net outcome of how labor productivity losses interact with crop and livestock yield changes. The interaction of human labor productivity losses in agriculture with crop yield losses is addressed by de Lima et. al. (2021) while heat stress impacts on the livestock sector is more challenging due to the wide variation in species and their responses to heat stress. Thus, the latter topic remains an area for further work.

It is also worth noting here that our analyses assess economic impacts in the context of the present-day economic structures, and therefore does not consider possible structural changes in the economy and how these might interact with the climate impacts. Not only are such changes difficult to predict, our approach is appropriate given that our objective is to identify and understand the economic mechanisms by which our economic outcomes of interest (labor allocation, trade effects, and poverty) are determined, as opposed to forecasting future outcomes.

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CHAPTER 2. HEAT STESS AND THE ALLOCATION OF LABOR BY AGRICULTURAL HOUSEHOLDS

2.1 Introduction

The economic implications of heat stress in humans are not a widely addressed aspect of global warming even though scientific studies in this area suggest alarming outcomes: half of all humans currently live in places that could become barely habitable at some point in an average year if global warming of 3-4°C occurs (Sherwood and Huber, 2010). This is because these places will experience combinations of heat and humidity that are not habitable without adaptative measures such as air-conditioning. Regions where heat and humidity combinations will be most adverse include much of South Asia and Sub-Saharan Africa. Thus, the (potentially) affected populations include the poorest people on Earth – rural households that engage in small-scale agriculture and rely to a large degree on outdoor manual labor. It is these poor, agricultural households that are the subject of this chapter. These are households with specific characteristics: they are simultaneously producers and consumers of agricultural products, and thus heat stress will affect them in more than one way; they will be affected as producers on the one hand and as consumers on the other. Furthermore, because of their low levels of wealth, these households are unlikely to be able to simply switch to heavily mechanized farming and air-conditioned homes. In this paper, we seek to assess how these households are likely to respond when faced with heat stress. We focus in particular on how their labor allocation between agricultural and non-agricultural uses will be affected. Our analysis determines the likely direction of the change in labor allocated to agriculture, and the mechanisms that determine this, by constructing a theoretical model of agricultural household decision-making that accounts for the effects of heat stress on production as well as consumption utility.

As noted, given that agricultural households are simultaneously producers, consumers and workers; heat stress will impact them in multiple ways. On the production side, heat stress will cause a loss of labor productivity/work capacity. Scientific studies in this area consistently estimate large labor capacity losses, ranging from 11% to up to 27% by 2050-80 depending on region (Dunne et. al. 2013, Kjellstrom et. al. 2009, Kjellstrom et. al. 2016), while Kjellstrom et. al. 2018 estimate losses of 4-12% under 2.7°C global warming. Thus, agricultural households are projected to experience a substantive production-side shock. The impact of this shock on labor demand in agriculture is ambiguous. On the one hand, there is a reason for optimal labor demand to increase – as each unit of labor becomes less productive, all else equal, the same level of output requires more labor, if labor is not easily substitutable with non-labor inputs. On the other hand, the new optimal production level could fall, and if this fall is sufficiently large then less labor may be required despite its decreased productivity. Thus, a priori, we do not know the direction of the shift in the demand for labor.

Furthermore, we postulate that heat-stress will not only affect labor productivity and hence labor demand, but will also affect work preferences, causing a shift in the supply of labor as well. That is, with increased heat-stress, manual labor such as that which poor households engage in for agriculture, will become less desirable, due simply to the increased unpleasantness of working in difficult conditions. All else equal, households would prefer to supply their labor to less manual, non-agricultural activities. Thus, agricultural households will experience both a shift in their demand for agricultural labor as producers, and a shift in their supply of labor as workers. Empirical observations of labor use in agriculture in the face of heat stress are therefore the net effect of these two, potentially opposing, shifts.

To develop a better understanding of these shifts in labor demand and supply, as well as their net effect on household labor allocations, we construct an agricultural household model with the necessary characteristics and use comparative statics to determine how such households can be expected to respond to labor heat stress. Agricultural household models (Sadoulet and de Janvry 1996; Singh, Squire and Strauss 1986), are a class of models that account for the fact that households that engage in agriculture are both producers and consumer-workers. They can fulfill their labor needs, as producers, with their own labor. Production decisions and consumption decisions thatinclude the consumption of leisure can thus become intertwined. As described above, heat stress acts as a shock to the household's production on the one hand, and a shock to the household's work preferences on the other. In our application, on the production side we model the household's production technologies to allow for labor-specific productivity changes. On the consumption side, we introduce a nested utility structure that allows for varying preferences for agricultural and non-agricultural work which determine work time allocation.

We then offer two types of analysis. First, we derive the household's optimal solutions mathematically and determine the theoretical consequences of changes in these solutions due to heat stress affecting labor. Second, we parameterize the model using data from a survey of agricultural households in Pakistan and determine the likely directions of changes among these households using simulation exercises in a computable version of the model. Furthermore, we consider the possibility that labor markets can be constrained in low-income rural economy contexts.

In response to these shocks, agricultural households can be expected to adapt in one (or more) of several ways. We can expect: (i) re-allocation of labor between agricultural activities and other uses; (ii) substitution of farm labor with capital (as far as technology permits); (iii) changes in crop-mix from labor-intensive crops to less labor-intensive crops; and (iv) migration. This study focuses on the first adaption channel: the re-allocation of labor between alternative uses, holding all other inputs fixed. This is arguably the least costly adaptive channel. The issues of changes in crop-mix and rural-urban migration are beyond the scope of this analysis. These are also the costliest adaption mechanisms and thus arguably the least common responses, under an assumption that catastrophic increases in global warming and heat stress are averted. We also note here that this paper only addresses household responses to mean global warming and the consequent increases in heat stress. Other aspects of climate change such as increased weather volatility, extreme events, water stress, increased conflicts, etc. are also beyond the scope of this paper.

The remainder of this chapter is organized as follows. Section 2.2 reviews literature closely related to our analysis. This includes a broad review of the scientific studies that assess the effects of heat stress on human labor capacity, and a review of the economic studies that have considered heat and climate change impacts on labor decisions. Section 2.3 broadly describes the canonical agricultural household model and our theoretical framework. Section 2.4 describes our specification of the agricultural household model. Section 2.5 describes the household survey data and the how we determine the model's parameters for the computable model. Section 2.6 presents our results and Section 2.7 provides a discussion of our findings.

2.2 Related Literature

2.2.1 Scientific Studies

Heat stress in humans is said to occur when the body loses its ability to regulate internal temperature, therebycausing physiological impairment. As the body's internal temperature rises, adverse effects occur including reduced cognitive and physical performance in addition to serious health risks. This is more likely to occur when high ambient temperatures combine with high humidity, which prevents the transfer of heat away from the body. As humidity increases, the effect of evaporative cooling – how much sweat and air flow can cool us – is reduced. Given human physiology, Sherwood and Huber (2010) find that if global mean warming of 7°C or more occurs, in some regions heat and humidity combinations begin to reach levels that exceed what humans could endure. The figure below shows the extreme scenario where global warming of 11-12°C occurs and serves to demonstrate the areas (colored in pink) that are most affected. These include South Asia, West Africa, and South America, where under this scenario, heat and humidity will be too high for human endurance. These zones account for 50% of the Earth's surface where people currently live, and populations in these regions include the poorest people and those that are heavily reliant on small-scale farming.

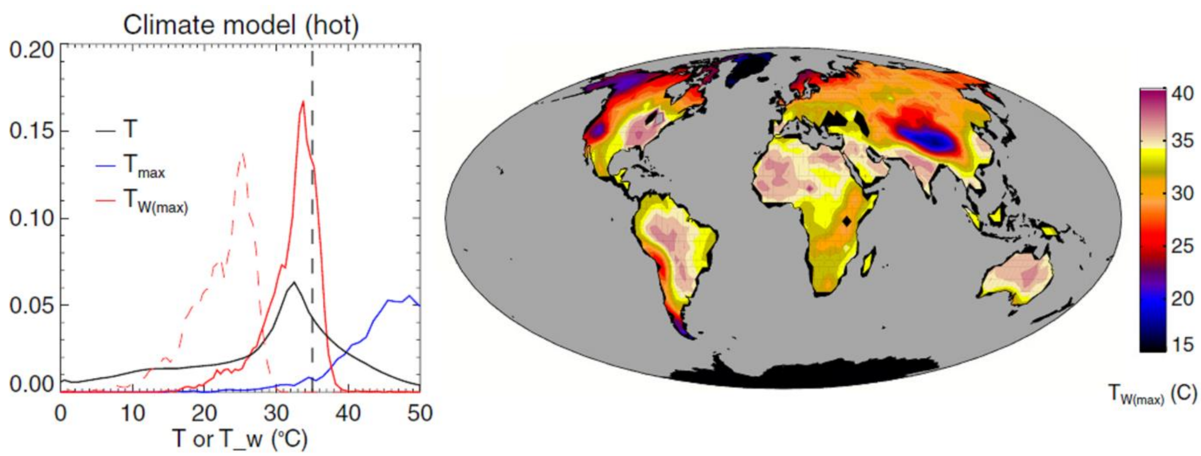

Figure 1: Distribution of temperature, maximum temperature, and T_w under a "hot" climate change scenario

Source: Sherwood and Huber (2010) **Note:** The wet bulb temperature, T_w, is a measure of heat stress that accounts for both heat and humidity. $T_w = 35$ is the most extreme upper limit that can be endured by human. The figure shows output from a from a high-CO2 model run of the slab-ocean version of the CAM3 climate model that produces a global-mean 12 °C warmer; accounting for GCM bias. Dashed line in the histogram shows historic distribution of T_w max.

Even under far more modest global warming scenarios, human labor capacity will be impacted. As noted earlier, a number of scientific studies estimate the extent to which human labor capacity might be affected using a variety of methods. All of these studies consistently point to non-trivial losses. Using international safety standards for workplace heat stress, Kjellstrom et. al. (2009) estimate that under a high CO2 scenario, some regions (e.g. Southeast Asia and Australasia) lose 18% of their labor capacity due to heat stress breeching safe levels. Other studies since then have reached similar conclusions: Dunne et. al. (2013) estimate that by 2200, under a high CO2 emission scenario, reductions in work capacity reach 37% during the hottest month and reductions of 5% occur even during the coolest months. Buzan (2018) considers a wide range of heat stress metrics and similarly concludes that: outdoor work during the day will be severely impacted by heat stress with only a few degrees of warming, while work during the night is also affected. Most recently, a study by Tigchelaar, Battisti and Spector (2020) that focuses on heat exposure faced by U.S. crop workers finds that the average number of days spent working in unsafe conditions will double by mid-century.

In short, the scientific literature suggests that human labor capacities across the world may be profoundly impacted by global warming. However, the economic literature on the implications of heat stress on human labor remains relatively underdeveloped. In the following section, we provide a broad overview of the economic literature in the area of heat and labor allocation decisions.

2.2.2 Economic Studies

Heal and Park (2013) use microeconomic theory to address the issue of the impact of heat alone on labor allocation decisions using microeconomic theory. They consider the utility maximization problem of a consumer-worker who must choose between leisure and work, as well as the level of effort exerted at work. The utility function includes core body temperature where they assume that utility is increasing in temperature initially but then decreasing in temperature beyond a certain threshold. Their model generates the proposition that when temperature exceeds a certain threshold, effort creates heat and disutility that may outweigh the benefits of the extra income generated. However, the consumer-worker framework does not address the choices and trade-offs of households who must also choose the labor they supply to their own-production activities.

Graff and Neidell (2014) address the heat-stress issues econometrically. They estimate the impacts of temperature on the allocation of time between work and leisure using American Time Use Surveys (ATUS). They find that when temperatures exceed 85°F, American workers in industries with high heat exposure reduce time allocated to labor by as much as an hour a day, allocating this time to indoor leisure. However, similar to Heal and Park (2013), their study considers only workers and the choice between work under paid employment and leisure.

A further study that looks at the effects of heat on migration is also mentioned here briefly since migration can be viewed as a re-allocation of labor as well; one that is constrained by costs and is arguably undertaken on a longer time frame. Mueller, Gray and Kosec (2014) using a panel dataset of households found statistically significant impacts of climate variables (precipitation, temperature, and floods) on household migration in Pakistan.

Finally, we also briefly mention here studies that assess the macroeconomic impacts of heat stress. Two recent studies use recursive-dynamic computable general equilibrium models that account for market responses and macroeconomic linkages. A study by Orlov et. al. 2020 (using labor productivity response functions and the– GRACE model: Global Responses to Anthropogenic Changes in the Environment) find that under the RCP8.5 scenario global GDP will decline by 1.4% in 2100 but regions such as South Asia and Africa experience greater losses of 3-6% of GDP. Finally, de Lima et. al. (2021) assess the welfare losses caused by human heat stress relative to losses caused by plant heat stress (yield losses caused by climate change) using the GTAP framework and find that human heat stress leads to economic losses that are on par with losses caused by heat stress in plants, but more sharply concentrated across the tropics.

2.3 Methodology

2.3.1 Agricultural household models

Given our focus on the labor choices of agricultural households in low-income countries, we begin with the canonical agricultural household model (Sadoulet and de Janvry 1996; Singh, Squire and Strauss 1986). The model posits a household that consumes two or more goods, where at least one is a home-produced agricultural good. The household's problem is to maximize utility derived from the consumption of these goods and leisure time, subject to the constraints posed by its production functions, its cash and time budgets, and exogenously determined prices and wages. Other constraints can be introduced, such as credit constraints, subsistence level production requirements, and constraints that account for missing or imperfect markets.

The solution to such a model has the following properties. If at most only one market is missing/imperfect, then utility maximization implies profit maximization. This means the household's problem is separable: the household behaves as though it first solves a profit maximization problem given its production function(s) and prices. This determines the households labor demand and production levels. Then, given maximized profits/income, the household solves its utility maximization problem, thus choosing its consumption levels of goods and leisure. In other words, production and consumption decisions are separable if markets are complete or if only one market is missing or imperfect. The formal proof of this is provided by Singh, Squire and Strauss (1986), and not repeated here. In this case, it is possible to obtain tractable mathematical solutions to the household's problem that can be signed easily by solving the household's profit-maximization problem and then utility maximization problem, recursively.

If, however, multiple markets are missing, the separability property fails. In this case, utility maximization does not imply profit maximization; the household may not be profit maximizing at its utility maximizing optimal. In other words, consumption decisions/preferences affect production decisions i.e., the two are non-separable. In this case, mathematical solutions tend to become complex even under relatively simple assumptions and functional forms, and numerical solutions/computable model simulations are typically used[1].

The evidence on whether the separability property holds or not in practice is somewhat mixed. Benjamin (1992) failed to reject the null hypothesis that family labor supply is independent of family composition in a sample of 4,000 households in rural Java, Indonesia; and hence concluded that these households could be treated as if their consumption and production decisions are separable. If labor markets are missing or imperfect, it should be the case that observed farm employment is correlated with the demographic composition of the household. However, LaFave and Thomas (2016) tested the same hypothesis using a new survey also of rural households in Java. They found empirical evidence to the contrary: the hypothesis that labor demand is unrelated to demographic composition is unambiguously rejected in their study. In our analysis, both possibilities are considered – that labor markets may or may not be perfect/fully integrated – described further in the following section.

[1] Taylor and Alderman (2003) provide a review of agricultural household models and their applications in past literature.

2.3.2 General approach

For our application, we consider two cases. In the first case, we proceed without any restrictions on the labor market. This assumes that households are able to find as much off-farm employment and/or labor for hire as desired. That is, labor markets are fully integrated. In the second case, we introduce a labor market constraint, considering the possibility that in low-income rural economies, households may be constrained in various ways e.g., off-farm jobs may not be available. More specifically, we assume that the labor market is entirely missing. In this way, our two cases cover two extreme cases.

Under the first case, the separability property is assured and allows for tractable mathematical solutions that aid in identifying and understanding the mechanisms at play. In the second case, with an additional labor constraint, and since we also hold non-labor inputs fixed to isolate only one margin of adaptation, separability fails and thus we rely on numerical solutions – we construct a computable version of our model, parameterize it based on a country case-study, and obtain numerical solutions to the household's problem given productivity and preference shocks as described above. The computable model and its parameterization are described in Section 2.5.

2.4 Conceptual framework

2.4.1 The framework in general terms

In our application of the agricultural household model, we begin by assuming that the household produces a field crop good (*a*) and a non-crop good (*n*). The non-crop good can be thought of as the output of a household micro-enterprise (e.g., rural households may engage in small-scale livestock rearing, wholesale/retail trade activities, production of non-agricultural home-produced goods for sale, provision of services to other households etc.). We assume that the household also makes purchases of a composite market good (*m*) that it does not produce itself. The household derives utility from the consumption of these three goods, as well as leisure time (*r*). Thus, in general terms, the household's objective is to maximize:

$$\max_{C_i} U = u(C_i; \theta_u(h)) \tag{1}$$

where $i = \{a, n, m, r\}$ is the set of goods and leisure, C_i is the consumption level of i, θ_u is a set of preference-related parameters, and $u(.)$ is a utility function increasing in all C_i. Thus, utility is increasing in the consumption of leisure, C_r, or equivalently decreasing in residual work time, $\mathrm{T} - C_r$ (where T is the household's endowment of time). The specification of this utility function and the preference parameters, θ_u , are discussed at greater length in the next sub-section. However, we note here that, given our proposition that heat stress affects preferences for labor (and hence preferences for leisure), elements of θ_u are assumed to be affected by heat stress, h.

The household's problem is to maximize utility in (1) subject to the following constraints. First, the household is constrained by its production technology:

$$Q_j = g_j\big(L_j, K_j\,;\, \gamma_j(h)\big) \tag{2}$$

where $j = \{a, n\}$ is the set of home-produced goods, Q_j the production level of good j, $g_j(.)$ is the production function of good j assumed to be increasing and concave in inputs of labor L_j, non-labor inputs K_j, and γ_j is a set of technology parameters . We assume γ_j includes factor-specific productivity parameters and where the productivity of labor is negatively affected by heat stress, h. This is achieved by assuming that $g_j(.)$ is a CES production function described further in the next section.

The household also faces a cash constraint that requires that total expenditures not exceed total revenues. Here, we assume exhaustion of income. Formally:

$$p_a C_a + p_n C_n + p_m C_m = p_a Q_a + p_n Q_n + w(L^w - L^h) \tag{3}$$

where p_i are exogenous market prices, w is the exogenously determined wage rate (which is equivalent to p_l, the price of leisure), L^h is total hired labor, while L^w is labor that is marketed (family time that is allocated to market wage employment). If L^w exceeds L^h then the household is a net supplier of labor. If, however, L^h exceeds L^w, then the household is a net hirer of labor. Hired and family labor are treated as perfect substitutes for one another.

The household's time constraint is given by:

$$\mathrm{T} = L^f + L^w + C_r \tag{4}$$

where T, as before, is the household's total endowment of time, L^f is family labor supplied to own production (of goods j), and C_r is the consumption of leisure.

The time and cash constraints, (3) and (4), are typically combined into a single "full-income constraint":

$$\sum_i p_i C_i = \sum_j p_j Q_j - w(L^f + L^h) + wT \tag{5}$$

where the right-hand side of (5) is "full income": farm profits plus the value of the household's time endowment. The household's problem thus reduces to maximizing utility, (1), subject to the full-income constraint (5), given fixed prices and wage.

2.4.2 Specific assumptions

In this section, we assume specific functional forms for the household's production and utility. This is necessarily more restrictive, but in return, we are able to say more about potential impacts of heat stress on agricultural households.

Production: We assume that the household's production technologies are characterized by constant elasticity of substitution, CES. Hence, the production level of good j given inputs of labor, L_j, and a composite of all other inputs, K_j, is given by:

$$Q_j = A_j\left[\left(\delta_j L_j\right)^{\rho} + \left(K_j\right)^{\rho}\right]^{\frac{1}{\rho}} \tag{6}$$

where A_j is a hicks-neutral productivity parameter, δ_j is a labor-specific productivity parameter, and ρ is the CES parameter such that the elasticity of substitution between labor and capital is given by $\sigma = \frac{1}{1-\rho}$. The CES production function allows for labor-specific productivity changes: we assume that heat-stress has the effect of reducing the productivity of labor alone. Formally, we assume labor productivity in sector j when j is the agricultural sector is decreasing with heat stress (H): $\delta_j = \delta(H)$ where $\delta'(H) < 0$.

We acknowledge that heat stress could also affect the productivity of other inputs as well – animal-power or even machinery used in crops are also likely to become less productive due to heat/heat stress. However, our assumption that labor alone is affected is consistent with these possibilities so long as we believe that labor productivity is affected more than other inputs. Similarly, for simplicity we assume that the home-production of the non-crop good is un-affected by heat stress which is consistent with the possibility that labor in the non-crop sector is affected as well, so long as crop labor is affected more.

Utility: As noted in the introduction, we posit that heat stress will have the effect of making agricultural/crop labor less desirable – all else equal, heat stress should cause households to supply less labor to crops. This requires a utility specification that captures preferences over kinds of work. We implement this as follows.

We begin by assuming, first, a utility function defined over the consumption of goods and leisure.

$$U = u(C_i) \tag{7}$$

where $i = \{a, n, m, r\}$. Then, given the optimal consumption of leisure, C_r^*, the family's total labor supply is the residual time left over from leisure:

$$L^s = \mathrm{T} - C_r^* \tag{8}$$

We assume that this total labor supply is allocated between crop and non-crop activities in a second stage based on relative preferences (or aversions) for crop and non-crop work. Assume relative preferences for agricultural work and other uses can be represented by positive scalars θ_a and θ_n, respectively, where $\theta_a + \theta_n = 1$. Furthermore, we assume that θ_a depends on heat stress. Thus, given the total amount of labor the household is willing to supply, L_s, we assume the proportion that is allocated to agriculture is given by:

$$L_a^S = \theta_a(h)L^S \tag{9}$$

where $\theta_a'(h) < 0$. That is, as heat stress increases, θ_a falls, causing a smaller portion of household labor supply to be allocated to agriculture.

This is similar to assuming a nested utility structure such that the household first determines its optimal mix of goods and leisure/non-work time (by maximizing the utility function u subject to a budget constraint). This determines residual work time. The household then determines the optimal split of this work time between agricultural and non-agricultural uses, given its relative preferences over these. That is, a second stage disutility minimization problem is solved: $\min v(L_j)$ subject to the constraint that $\sum L_j = T - C_r^*$ where we have effectively assumed for simplicity that $v(.)$ is of a Cobb-Douglas form which results in fixed proportions of work time being allocated to each use. Under these assumptions, work preferences and labor demand are only related through changes in income. More specifically, heat stress-related productivity changes will impact labor demand, production, and hence income. In turn, income changes result in changes in leisure consumption and hence total work time. Preference over different work do not affect these production decisions and income outcomes, only how the household allocates its work time (once leisure consumption decisions are already made).

This treatment of work preferences is sufficient to capture the necessary proposition: that all else equal, (family) labor supplied to agriculture should fall with heat stress due to a shift in preferences over crop and non-crop work.

The approach we have employed, thus, accounts for the effects of heat stress on both production as well as preferences on the consumption side. However, heat stress may potentially have accumulated effects that are unaccounted for: workers who continue to allocate some of their work time to production in the heat stress affected sector, may need to allocate more of their "leisure" time to additional necessary rest. Our assumption that family labor time can simply be apportioned differently between sectors may not fully reflect the impacts of heat stress. However, the effects of accumulated heat stress are not easily quantified and we therefore leave this aspect for future work.

2.4.3 Analytical solutions with unrestricted labor markets

The model as described thus far assumes that labor markets are fully integrated such that the household is free is to alter its net hiring of labor without constraint. Given that we assume non-labor inputs are fixed, and that there is one single composite crop, we are isolating one single margin of adaption to heat stress: the re-allocation of labor between crop production and other uses. Under these assumptions, the separability property holds, since households are still able to profit maximize. In this case, the household's profit maximization and utility maximization can be solved separately, and tractable analytical solutions obtained. This allows us to identify the mechanisms that determine directions and magnitudes of changes. These analytical solutions are as follows.

Profit Maximization: Assuming independent production functions of the two home-produced goods, and with labor the only variable input, the profit maximization problem for good j is to $\max_{Q_j, L_j} p_j Q_j - wL_j$ where Q_j is constrained by the production function in (2). Assuming hired and family labor are perfectly substitutable, L_j includes both family and hired labor used in the home production of good j. The first order condition with respect to L_j requires that the value of the marginal product of labor equal the wage rate:

$$p_j \frac{\partial Q_j}{\partial L_j} = w \tag{10}$$

This yields the conditional demand for labor in sector j of the form:

$$L_j^D = f\left(Q_j\left(\gamma_j(h)\right); p_j, w, \gamma_j(h)\right) \tag{11}$$

This expression illustrates that heat stress affects demand for labor (in sector j) in two ways. There is a direct effect as productivity of labor falls, as well as an indirect effect that depends on how the level of production is affected by the loss of productivity, $Q_j\left(\gamma_j(h)\right)$ (i.e., whether the optimal production level increases or decreases as a result of heat stress induced labor productivity loss). Assuming that the production function is of CES form (equation 6), then the specific form of the conditional labor demand function is as follows.

$$L_j^D = Q_j\left(\delta_j A_j\right)^{\sigma_j - 1}\left(\frac{p_j}{w}\right)^{\sigma_j} \tag{12}$$

Taking total derivatives and writing this in terms of proportionate changes yields a more informative expression:

$$\widehat{L_j^D} = \widehat{Q_j} + (\sigma_j - 1)\widehat{\delta_j} + (\sigma_j - 1)\widehat{A_j} + \sigma(\widehat{p_j} - \widehat{w}) \tag{13}$$

where hats denote proportionate changes (e.g., $\hat{L}_j = dL_j/L_j$). Thus, with a change in heat stress, assuming that households are price takers and holding total factor productivity, A_j, constant (i.e., $\widehat{p_j} = \widehat{w} = \widehat{A_j} = 0$), the resulting change in labor demand in sector j depends on two effects. The first can be described as a substitution effect measured by $(\sigma_j - 1)\widehat{\delta_j}$ where we assume that productivity of labor falls due to heat stress (i.e., $\widehat{\delta_j} < 0$) in the heat stress-affected sector. The direction and the magnitude of this effect depends on the sector's substitution parameter, σ_j, where if this is small ($\sigma_j < 1$), labor demand will increase for a given a level of output. The second is an expansion/contraction effect, measured by $\widehat{Q_j}$. By taking total derivatives of the production function, and noting that $\widehat{K_j} = 0$ by assumption, this is given by:

$$\hat{Q}_j = \hat{A}_j + S_L\left(\hat{\delta}_j + \hat{L}_j\right) \tag{14}$$

where $S_L = \frac{(\delta_j L_j)^{\rho_j}}{(\delta_j L_j)^{\rho_j} + (K_j)^{\rho_j}}$ is a measure of the share of labor relative to other inputs in the benchmark. A larger initial share of labor relative to other inputs will therefore create a larger push towards a contraction of production when heat stress causes $\widehat{\delta_j} < 0$.

An expression for the unconditional demand for labor can be obtained by substituting $\hat{Q}_j$ in equation 13, and re-arranging:

$$\hat{L}_j^D = \left(\frac{\sigma_j}{1 - S_L^j}\right)\hat{A}_j + \left(\frac{\sigma_j}{1 - S_L^j} - 1\right)\hat{\delta}_j + \left(\frac{\sigma_j}{1 - S_L^j}\right)\left(\hat{p}_j - \widehat{w}\right) \tag{15}$$

Thus, the net impact on labor demand, when δ_j changes (and all else equal), depends on the relative sizes of the substitution parameter σ_j and the initial share of labor in the benchmark, S_L. Labor demand, L_j, will <u>increase</u> due to heat-stress-induced productivity loss if $\left(\frac{\sigma_j}{1 - S_L^j} - 1\right) < 0$ or

$$\sigma_j < 1 - S_L^j \tag{16}$$

That is, labor demand is likely to increases if its substitutability with other inputs is low while the share of non-labor inputs is large.

Result 1: *All else equal, the response of labor demand in sector j to heat stress-induced labor productivity loss in that sector is theoretically ambiguous. The direction of change depends on the sector's relative sizes of the share of non-labor inputs in the base case and the degree of their substitutability with labor. If $\sigma_j < 1 - S_L^j$ then the* *demand for labor in the heat stress-affected sector will increase. Else, it will decrease.*

Whether or not the condition in Equation 16 tends to hold in practice is considered more closely in Section 2.6.1.

Furthermore, if instead we also consider that general equilibrium effects will cause changes in prices and wages (such that $\hat{p}_j, \hat{w}$ are not zero), the direction of change in the demand for labor has further ambiguity. In the last term in equation 15, while the coefficient $\left(\frac{\sigma}{1-S_L}\right)$ is strictly positive, the sign of the expression $(\hat{p}_j - \hat{w})$ is indeterminate (exogenous in our framework). We also note here that the first term in (15) will also be non-zero in reality, considering that heat stress will also affect crop yields which can be translated as a change in the total factor productivity parameter, $\hat{A}_j$. The effects of climate change on crop yields as well as their wider impacts have been previously studied in the literature (see for example, Hertel et. al. 2010; Lobell et. al., 2008; Loyd et. al., 2011) and are outside the scope of this study. We only note here that these can be assumed to be negative in regions such as South Asia, Southeast Asia, and Africa where temperatures are already high.

To see how output is affected, we can obtain an expression of the change in output at the optimum by substituting $\hat{L}_j$ in equation 14. This yields

$$\hat{Q}_j = \left(\frac{1 + S_L(\sigma_j - 1)}{1 - S_L}\right)\hat{A}_j + \left(\frac{S_L}{1 - S_L}\right)\sigma_j\hat{\delta}_j + \left(\frac{S_L}{1 - S_L}\right)\sigma_j(\hat{p}_j - \hat{w}) \qquad (17)$$

Thus, if we hold all else equal ($\hat{A}_j = \hat{p}_j = \hat{w} = 0$), output falls unambiguously since S_L, $(1 - S_L)$, and σ are all positive.

Result 2: *From (17), all else equal, sector j's output falls unambiguously in response to heat stress-induced labor productivity loss in that sector.*

However, in general equilibrium there is ambiguity. As before, $\hat{p}_j - \hat{w}$ is of indeterminate sign within our microeconomic/household framework and depends not only on aggregate demand

and supply effects but also on resource competition across the domestic economy as well as trade affects not considered here.

Finally, the change in the household's profits and thus income, holding prices and wages fixed, depends on the change in output relative to the change in labor use:

$$\hat{\pi}_j = \hat{Q}_j - \hat{L}_j \tag{18}$$

In response to an adverse shock such as heat stress, we would expect that households' incomes would be negatively impacted. However, equation 18 shows that this is not an unambiguous result in our theoretical model. We know that while output falls unambiguously (in the absence of general equilibrium effects), labor demand may increase or decrease when $\hat{\delta}_j < 0$. Hence, household income/profit falls only if $\hat{Q}_j < \hat{L}_j$. That is, if either (i) labor demand increases (since $\hat{Q}_j$ is unambiguously negative), or (ii) labor demand decreases but the decrease in output is larger. The first condition is met so long as the condition in 16 holds (small sigma and small labor share). Or, if this is not the case (and labor demand does not increase), for profits (in sector *j*) to fall we require (from equations 15 and 17):

$$\left(\frac{S_L}{1-S_L}\right)\sigma_j\hat{\delta}_j < \left(\frac{\sigma_j}{1-S_L} - 1\right)\hat{\delta}_j$$

Or (since $\hat{\delta}_j$ is negative under heat stress):

$$\left(\frac{S_L}{1-S_L}\right)\sigma_j > \left(\frac{\sigma_j}{1-S_L} - 1\right)$$

This implies

$$\sigma_j S_L > \sigma_j - (1 - S_L)$$

$$\sigma_j S_L - \sigma_j > S_L - 1$$

$$\sigma_j(S_L - 1) > (S_L - 1)$$

$$\sigma_j < 1 \tag{19}$$

That is, the parameter space within which profits to sector *j fall* is $\sigma_j < 1$.

Result 3: *Given equation (18), and results 2 and 3, household profits and income will fall if demand for labor in the heat stress affected sector increases (i.e. if condition (16) holds for the sector). If, however, (16) does not hold (and labor demand decreases), incomes will still fall if (19) holds. Household profits and thus income could theoretically increase if substitutability of labor with other inputs is high ($\sigma_j > 1$) in the heat stress-affected sector.*

The intuition behind result 3, and the possibility that incomes could increase as a result of heat stress/labor productivity loss lies in the fact that we hold non-labor inputs to be fixed (sector-specific). Profits/returns to fixed factors therefore would increase if labor demand were to fall by more than the fall in output.

Utility Maximization: Given the household's optimal labor demand, production, and income from the profit maximization problem above, the household's optimal consumption choices can then be solved for. This entails maximizing its utility subject to its full-income constraint in which farm profits are set equal to optimal, profit-maximizing profits obtained in the first step. That is, the household's problem is to maximize:

$$U = u(C_i) \tag{20}$$

subject to:

$$\sum_i p_i C_i = Y^* \tag{21}$$

where $Y^* = \sum_j \pi_j^* + wT$ and π_j^* are optimal profits from the profit maximization problem. (The price of leisure in (21) is equivalent to the wage rate, $p_r = w$).

If profits fall as a result of heat-stress-induced productivity losses, and leisure is a normal good, then consumption of leisure will fall, and total family time allocated to work (or the household's labor supply) increases since $L^S = \mathrm{T} - C_r^*$. Say, u is of Cobb-Douglas form where the preference/share parameter for leisure is β_r. Then, optimal demand for leisure is given by:

$$C_r^* = \beta_r \frac{Y^*}{w} \tag{22}$$

In this case the consumption of leisure falls and total labor supply increases by the same percentage as the fall in income. Combining this with our assumption in (9) that the portion of work time allocated to agriculture is θ_a which is declining in heat stress, we have that:

$$L_a^{S^*} = \theta_a(h)\left(\mathrm{T} - \beta_r \frac{Y^*}{w}\right) \tag{23}$$

Or in percentage changes:0

$$\hat{L}_a^S = \hat{\theta}_a - S_R \widehat{Y^*} \tag{24}$$

where $S_R = \frac{\frac{\beta_r Y^*}{w}}{\mathrm{T} - \frac{\beta_r Y^*}{w}}$ is the ratio of the value of leisure time to the value of work time in the benchmark.

In the absence of a preference shift, the household's labor supplied to agriculture increases by $-S_R\widehat{Y^*}$ (if income falls so that $\hat{Y}^*$ is negative). Thus, for family labor supplied to agriculture to instead decrease would requires a preference shift that is smaller (more negative). That is, if $\hat{\theta}_a < S_R\widehat{Y^*}$ **.** This condition is more easily met if the share of the value of leisure time in the benchmark is low relative to the value of goods consumption (S_R is low), and/or if the decline in income is small.

Result 4: *If leisure is normal and incomes fall, labor supplied to both own production activities will increase. However, a decline in the preference for the heat affected activity that is large relative to the decline in income, and/or if the share of leisure consumption in the base is low, could cause a decline in family labor supplied to the heat affected sector. That is, if* $\hat{\theta}_a < S_R\widehat{Y^*}$.

However, this result is dependent on our assumption regarding the functional form of the utility function $u(C_i)$ or more specifically, what we assume about the nature and responsiveness of leisure demand to changes in income. By imposing a Cobb-Douglas utility function, we have assumed leisure is normal and has a fixed share in full-income. Assuming that leisure is normal is arguably valid when the households in question are low-income households who are unlikely to lie on the backward bending part of their labor supply curve. Assuming leisure has a fixed share in full income is the more stringent assumption but given our goals of simply understanding the mechanisms at work, this assumption avoids un-necessary complexity.

Marketed Labor: Thus far we have not addressed the household's hiring or wage employment decisions. These are determined as follows. For each sector, j, we know the household's demand for labor, L_j^D from the profit maximization problem. And, from the utility maximization problem, we know the household's consumption of leisure time, which in turn determines the residual time leftover for work activities. Given our assumption that there are no labor market constraints to hiring or wage employment, if the household's total demand for labor for exceeds what it is willing to supply, that is if $\sum_j L_j^D > T - C_r$, then the household hires additional labor. If the opposite is true, then the household will market the excess of its labor supply for off-farm wage employment. Formally, L^m, the amount of family time that is marketed is

$$L^m = (L_a^S - L_a^D) + (L_n^S - L_n^D) \quad (25)$$

where if L^m is negative, the household is a net hirer of labor. If L^m is positive, then the household is a net supplier of labor (to the wage labor market).

2.5 Computable model and data

Next, we turn to the possibility that rural households in low-income economies face labor market constraints. As noted previously, we rely on numerical solutions using a computable model in this case, as follows.

2.5.1 Household data

For the numerical analysis, a computable version of the model is developed in GAMS and parameterized using data from a 2012 survey of rural households in Pakistan (IFPRI & IDS, 2016). As Chapter 4 will show, Pakistan is among the countries that will be most affected by heat-stress-induced labor capacity losses. It is also an economy that is agrarian with significant portion of farms that are less than 5 acres. Furthermore, the availability of the aforementioned survey which contains significant details about family labor use, made Pakistan a suitable case for this study. The survey covers approximately 2,000 households of which we use a sub-sample of 480 households that can be considered "agricultural households" consistent with our theoretical model: households that (profitably) engage in own-farm crop production and as well as production of (at least one) non-cropping good/service (e.g., livestock, and other non-agricultural household micro-enterprises). Table 1 describes how this sub-sample is obtained. We begin with 976 households that cultivated land in the survey years (i.e., are crop producers). However, several exclusions reduce this to 480.

Table 1: Determination of the household sample for the numerical analysis

	Number of Households	Note
Households that reported cultivating land (crop producers)	976	
Excluding households that reported lost crops due to floods or zero production	905	
Excluding households that are extreme outliers in terms of value of production per acre and/or value of labor per acre [> mean + 4*(std. dev.)]	892	Valid HHs
Excluding households with negative returns to non-labor inputs in their non-crop production	754	15% of valid HHs (892) have negative returns
Households that are both crop and non-crop producers	678	90% of 754
Excluding households with negative returns to non-labor inputs in non-crop production	616	70% of valid HHs
Excluding households with zero/missing labor data in non-crop production	586	
Excluding HHs with zero/missing work data for all family members (HHs with zero work hours)	480	

Descriptive statistics of excluded households

The most significant exclusion in Table 1 is of 138 households whose returns to non-labor inputs in their cropping activities turn out to be negative in our estimation. (The estimation of returns to non-labor inputs is described in later sections.) These households cannot be included since the implied share of non-labor inputs, K_j, in the crop production function is negative for these households. These households are approximately 15% of households that successfully harvested all of their crops in the survey year (i.e., did not report a total loss of any crop). Their negative returns could be the result of a bad cropping year (low yields due to weather, pests etc.), or data collection errors, or measurement errors since wages for family labor must be imputed (as described later). On the other hand, we are potentially excluding some of the poorest households – these are potentially households with no viable alternative other than to supply their labor to agriculture despite negative returns[2].

Table 2: Descriptive statistics of excluded households

	Median	*Mean*	*Std. Dev.*	*Min.*	*Max.*
Farm size (Acres)	2.0	3.9	4.7	0.2	32
Value of crop production (PKR[1])	74,650	126,438	170,817	3200	1,363,675
Value of crop production per acre (PKR[1])	27,800	38,975	33,797	1,917	194,810
Value of labor used in crop production (PKR[1])	122,834	203,216	270,380	3664	2,009,004
Value of labor used in crop production per acre (PKR[1])	51,603	73,789	67,668	3,545	323,414
Returns to non-labor inputs in crop production (PKR[1])	-30,696	-76,778	133,775	-1,154,790	-428

Comparing descriptive statistics of these 138 excluded households (in Table 2 above) with the 480 that we do include (Table 3), we find that the median farm size of households that we exclude is 2 acres, while the median farm size of included households is 5 acres. That is, excluded households tend to be much smaller in farm size. Furthermore, the value of their crop production per acre (PKR 27,800) is much lower than that of households that we include in our sample (PKR 46,992). At the same time, their value of labor used per acre is much higher. Excluded households use PKR 51,603 worth of labor per acre, while included households use only PKR 12,344 per acre. These patterns (small farm sizes with low value of output while labor use is high) could be consistent with especially poor households without access to off-farm opportunities. It could however also be reflective of a bad cropping year. That these households are not included is a limitation of the framework/analysis in this study.

[2] Our model lacks access to credit, storage, and transfer income which could be possible explanations of these negative returns. However, access to formal credit markets is uncommon among rural households in Pakistan. Grain storage is a possibility although these tend to be subject to significant storage losses. (see e.g. Ricker-Gilbert et. al. (2022))

Table 3: Summary statistics of model variables in sampled agricultural households

	Median	*Mean*	*Std. Dev.*	*Min.*	*Max.*
Farm size (Acres)	5.0	8.6	11.2	0.2	110
Value of crop production (PKR[1])	253,516	516,256	758,127	7,200	7,092,920
Value of crop production per acre (PKR)	46,992	70,076	73,707	3,200	627,000
Value of non-crop production (PKR[1])	145,257	213,889	220,491	1,430	1,470,853
Value of Crop Production to Non-crop Production (Ratio)	1.8	3.5	6.7	0.03	104
Value of labor used in crop production (PKR[1])	65,504	11,0361	119,483	2,483	894,268
Value of labor used in crop production per acre (PKR[1])	12,344	20,809	29,715	464	284,343
Value of labor used in non-crop production (PKR[1])	28,971	43,774	64,828	62	840,415
Returns to non-labor inputs in crop production (PKR[1])	157,459	405,894	701,037	1,078	6,655,133
Returns to non-labor inputs in non-crop production (PKR[1])	107,577	170,114	197,731	801	1,301,750

Notes: [1] One USD = Approx. 105 PKR in 2011-2014

Descriptive statistics of sample households

In Table 1, after excluding households that were estimated to have negative returns to non-labor inputs in their cropping activities; we find that most households tend to be diversified. Of the 754 remaining households, 678 (or 90%) also engage in non-cropping production with livestock-rearing being the most common non-crop activity (98% of 678 engage in livestock rearing). However, similar to our treatment of crops, we are forced to exclude households that are estimated to have negative returns (to non-labor inputs) in their non-crop production activities (as a whole). This reduces the sample further to 616 households that fit our definition of an "agricultural household" engaging in both crop and non-crop production activities (with positive residual returns to non-labor inputs in both activities). However, significant amounts of missing family labor-use data reduce the final useable sample further to 480.

In this final useable sample of 480 households, the median farm-size is 5 acres (Table 3) and a quarter of households are smaller than 2.5 acres (not shown). The median (annual) value of crops produced is 253,516 Pakistani Rupees (or approximately 2,400 2012 U.S. dollars). The median value of non-crop production is PKR 145,257 or roughly half of crop production. Summary statistics of the value of labor (both hired and family) are also presented in Table 3. These estimates suggest median returns/profits (to non-labor inputs) are PKR 157,459 in crop production and PKR 107,577 in non-crop production in our sample.

2.5.2 Parameterizing production functions

Crop Production: For each household, we determine values of their total crop output (Q_a) using all crop production (including that kept for home consumption, seed, livestock or given away as gifts or in-kind payments). Crops are valued using reported sales prices (any missing prices are imputed based on crop and location). The value of hired labor in agriculture (L_a^h) is obtained directly from reported numbers of persons hired and cost per person. These data are also used to determine the wage rate for crop labor in general. This wage rate is then also used to estimate the value of family labor (L_a^f). The survey captures family days spent on cropping activities in detail. (For household's that do not hire labor, wages are imputed based on location). The value of non-labor inputs in crops (K_a) is then calculated as the difference between the value of crop production and the value of labor inputs.

Non-crop production: The value of non-crop production (Q_n) consists largely of livestock for a majority of households but also includes reported revenues from any other businesses owned by any family member. The value of livestock production is determined as the sum of: (i) net sales of animals (i.e., value of animals sold or slaughtered less value of animals purchased), (ii) value of animals born in the year in question (i.e., the value of young animals), (iii) value of all poultry, and (iv) the value of all livestock products produced (milk, eggs etc.). Furthermore, we also include (v) an annualized value of non-poultry adult animals (which consist mainly of buffalo, cows, goats, and sheep). The annualized value is based on rough estimates of animal life cycles in farming in Pakistan (e.g., cows tend to be kept for milk and put to slaughter in approximately10 years. We therefore include 1/10th of the value of cows owned). The value of labor used for livestock or other business includes the cost of labor hired (L_n^h), and family labor used (L_n^f) where family labor is valued using reported wages earned from off-farm livestock-related employment and wages earned from other jobs for non-livestock business labor (any missing wages are imputed based on location). The residual value of production, $Q_n - L_n^h - L_n^f$, is treated as the value of non-labor inputs (K_n).

Elasticities of substitution: In addition, we also require values of σ_j, the elasticities of substitution between labor and non-labor inputs in crop and non-crop production. Our analytical findings indicate that this a key parameter, and labor-demand results will be sensitive to choices of σ_j. For greater generalizability of our findings, we therefore use three different sets of estimates of σ_j's, described as follows.

In applications of IFPRI's standard CGE model for Pakistan (see for example Debowicz et. al., 2012), the elasticity of substitution for crops is set to 0.9 and the elasticity of substitution in non-agricultural sectors is 0.75.[3] In contrast, elasticities of substitution in the standard GTAP model are much lower for crops (0.26) and relatively high in livestock and non-agriculture (1.47). The GTAP input substitution elasticities are in turn based on global estimates from (Jomini et. al, 1994). Thus, estimates that are specific to Pakistan cover a wide range. As further points of comparison: a study by Wei (2013) estimates the elasticity of substitution between labor and capital in Indian agriculture, which is a comparable economy, to be around 0.44; while Okagwa and Ban (2008) estimate the substitutability of capital-energy and labor in agriculture in a panel of developed countries and also find these to be not very high (around 0.55)[4]. For our analysis, we avoid favoring a particular estimate and instead take the approach of using three alternative sets of elasticities listed in Table 4. We focus on results obtained using GTAP and IFPRI elasticity estimates. Additionally, we also consider the case where the elasticity of substitution in both crop and non-crop production is 1 as a useful point of comparison in our analysis.[5]

[3] The underlying sources of these values used in the IFPRI standard model for Pakistan are not clear.
[4] These estimates also aggregate livestock and crops into a single agricultural sector, and thus elasticity estimates for crops alone may be lower.
[5] In a study estimating capital-labor substitution elasticities across industries in the U.S., Balistreri et. al. (2002) find that the Cobb-Douglas specification, including for agriculture, cannot be rejected and recommend using this as transparent starting point.

Table 4: Alternative values of elasticities of substitution in crop and non-crop production

	Crops	*Non-crops*
GTAP elasticities	0.26	1.48
IFPRI elasticities	0.90	0.75
Cobb-Douglas elasticities	1.00	1.00

2.5.3 Parameterizing utility

Consumption budget shares (β_i) were obtained using reported consumption spending on various goods ($\beta_i = C_i / \sum_i C_i$) and where the value of the consumption of leisure (C_r) was estimated as follows. The "quantity" of leisure consumed was estimated by subtracting the family's reported time spent on work activities (own farm activities, own livestock activities, own business, and wage employment)[6] from the family's endowment of time/leisure (T_w).

The family's endowment of time/leisure (T_w) is considered to be the household's total potential hours (in a year) that are available to be allocated between leisure, crop production activities, non-crop production activities, and wage employment. Time that must be allocated to essential rest, food consumption, and essential household chores, commuting etc. must be excluded. To do this, we make the following assumptions. We assume women have fewer allocable hours in a day than men considering time taken up by essential household chores and family care activities. Specifically, we assume (rural) women (in Pakistan) have 6 hours in a day that are available for allocation. For men, we assume 12 hours in a day are available for allocation. Thus, a household's total annual endowment of time is calculated as the number of working age women times 6 hours times 365 days plus the number of working age men times 12 hours times 365 days.

As noted above, we then subtract the household's total reported work hours from its endowment of time to obtain the level/quantity of leisure consumed in the base. The monetary value of leisure is then estimated by using the household's average wage rate from any paid employment activities. When missing, this wage rate is imputed based on location.

[6] Note that the PRHPS survey captures time spent on own production activities in a detailed manner (number of days and hours per day for each household member spent on specific crop and livestock activities on own-farm as well paid off-farm). Time spent on permanent jobs and own business was calculated assuming 8 hour work-days (number of days and months are captured by the survey)

2.5.4 Experimental design

To simulate the impact of heat stress on labor in the numerical/computable model, we assume that productivity of labor in crops (δ_a) falls by 20%. This is consistent with estimated labor capacity losses in agriculture in Pakistan if mean global temperatures were to rise by 3°C (see Chapter 3). The computable household model described above is run 2 x 480 x 2 times – using two sets of elasticities (as described in the preceding sections), solving it separately for each of the 480 households sampled. Furthermore, we consider two different labor market scenarios: (i) by implementing the model as is in Section 2.4, assuming labor markets are fully integrated; (ii) we consider the other extreme where the labor market is entirely missing such that each household's net marketed supply of labor is fixed at observed baseline levels.

2.6 Numerical results

2.6.1 Household data

The analytical solutions derived in the theory section highlight how a few key parameters play an important role in determining the directions and magnitudes of households' responses. Descriptive statistics for the model's parameters estimated from the household samples are summarized in Table 5. On the consumption side, the mean share of crop consumption is 12%, the non-crops consumption share is also 12% (this is comprised primarily of meat and livestock products since these are the most common self-produced non-crop good), all other (non-home-produced market) goods account for 21% of full household income, and leisure accounts for the remainder (56%). (Note that these are shares of "full income" rather than cash income. The calculation of the value of leisure was described in Section 2.5.3). The share of leisure appears high, but this could be reflective of low levels of money income and hence low levels of consumption of goods.

Table 5: Estimated consumption and production parameters for sampled households

	Median	*Mean*	*Std. Dev.*
		Consumption Shares (%)	
Crops	11.3	11.9	5.4
Non-crops	10.7	12.4	7.6
Market goods	19.8	21.2	9.9
Leisure	55.6	54.5	15.8
		Crop Production - Input Shares (%)	
Labor	28.8	33.9	22.8
Capital	71.2	66.1	22.8
		Non-Crop Production - Input Shares (%)	
Labor	20.0	26.9	21.3
Capital	80.0	73.1	21.3

On the production side, in light of the analytical findings of the previous section, we know that the share of non-labor inputs is a key parameter that will determine directions of changes. Recall Result 1 where we found that if $\sigma_j < 1 - S_L^j$ then the demand for labor in the heat stress-affected sector will increase, where the right-hand side is the share of non-labor inputs in the sector. In Table 5, we see that the mean share of non-labor inputs in crop production is 34% while the median is 29%. Figure 2 shows the distribution of this share for crops $(1 - S_L^a)$ estimated from the household data, compared with alternative estimates of σ_a (the elasticity of substitution parameter for crops). Recall that in the GTAP model, the elasticity of substitution employed for cropping sectors is 0.26 while IFPRI employs a larger estimate of 0.9. We see that, for the vast majority of households (over 90%), the GTAP elasticity for agriculture (0.26) is less than the estimated share of non-labor inputs in the data – and hence we can expect that the demand for labor in agriculture will generally increase. However, the opposite is true if we rely on the IFPRI elasticity of 0.9 – in this case the elasticity is generally larger than the share of non-labor inputs, and hence labor demand in agriculture will generally fall.[7]

[7] In the case where we assume Cobb-Douglas production functions, $\sigma_a = 1$, the share of non-labor inputs is necessarily smaller, and an increase is crop labor demand in response to heat stress is not possible.

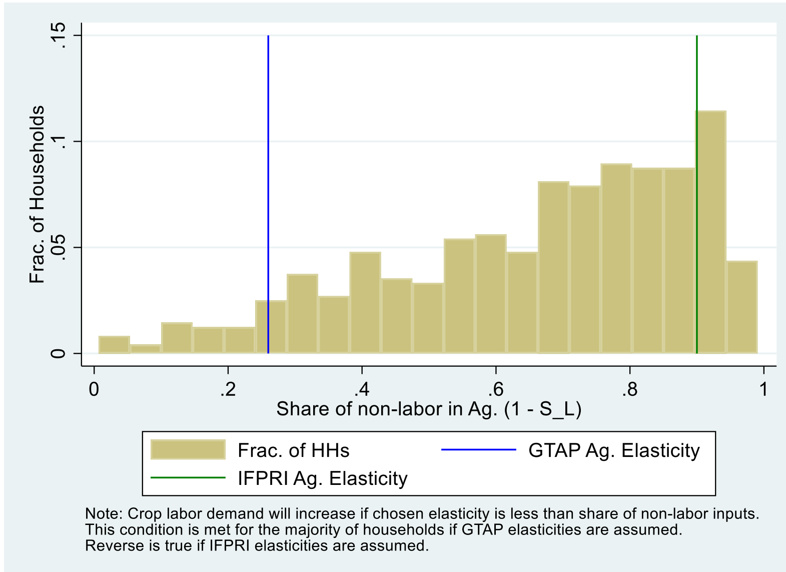

Figure 2: Observed shares of non-labor inputs in agricultural production ($1 - S_L^a$) across 480 agricultural households in Pakistan compared with input elasticities (σ_a) from GTAP and IFPRI sources

2.6.2 Numerical solution with integrated labor market

In section 2.4.3, we derived analytical solutions to the household model as formalized in Section 4.2.2 where we assumed that the household faces no constraints in the market for labor. That is, the household is free to hire as much labor and/or market as much of its family labor as needed (to maximize income and utility). In this section, the solution in this case (of fully integrated labor markets) is now assessed numerically using the computable model parameterized using our sample of agricultural households from Pakistan (described in Section 2.5).

Labor demand for own production: As expected, the demand for labor in crop production increases in 90% of the households in our sample in the case where the elasticity of substitution in the crop production function is set to 0.26 (GTAP elasticities). In the cases, where σ_a is set to 0.9 (IFPRI elasticities) or 1 (Cobb-Douglas specification), this result is reversed as expected: demand for labor for crop production increases for only 14% or 0% of households, respectively. (See Table 6 and Figure 3). These results illustrate that the size of the input substitution elasticity is the key driver of labor demand changes (with a given distribution of non-labor inputs).

Table 6: Demand for labor for own-production activities under integrated labor market

	*HHs with **increased** labor demand*	*HHs with **decreased** labor demand*	***Mean** change in labor demand*	***Median** change in labor demand*
With GTAP based elasticities ($\sigma_a = 0.26, \sigma_n = 1.48$)				
Crops	90.0%	10.0%	8.7%	14.8%
Non-crops	-	-	-	-
With IFPRI based elasticities ($\sigma_a = 0.9, \sigma_n = 0.75$)				
Crops	13.6%	86.4%	-12.7%	-5.9%
Non-crops	-	-	-	-
With Cobb-Douglas elasticities ($\sigma_a = 1, \sigma_n = 1$)				
Crops	0.0%	100%	-15.4%	-8.7%
Non-crops	-	-	-	-

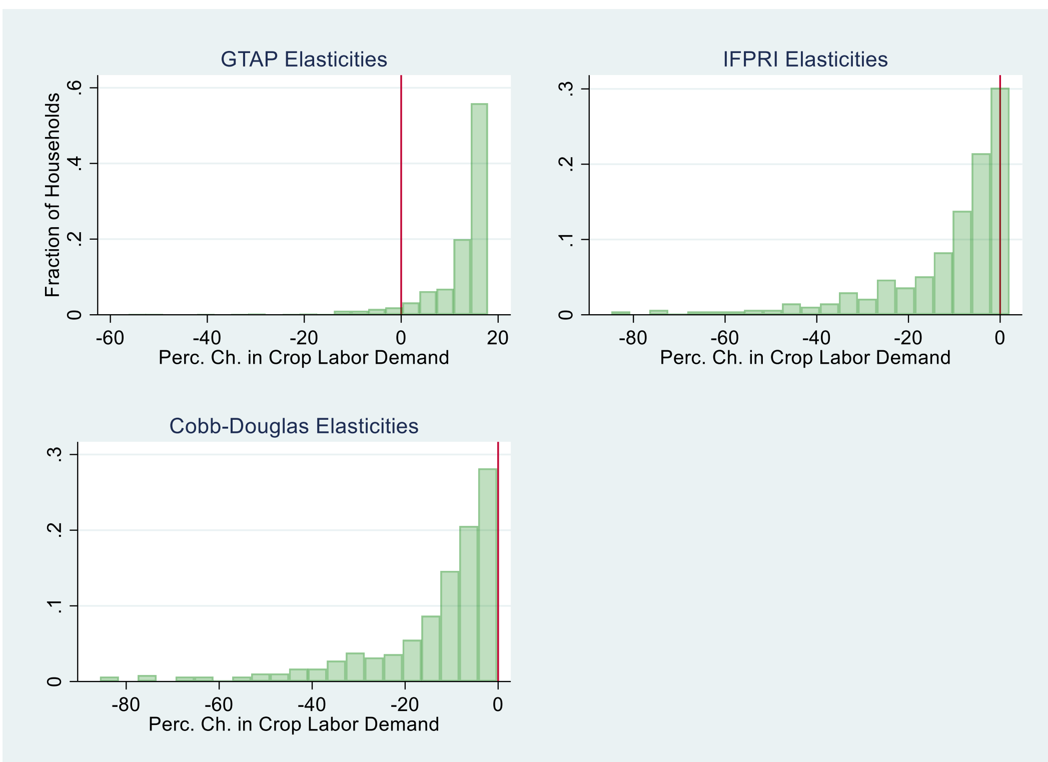

Figure 3: Distribution of percentage changes in crop labor demand with integrated labor market

Note that, in Table 6, labor demand for non-crop production is unaffected in the case where labor markets are fully integrated (consistent with our analytical results), and only the input elasticity in crop production is relevant. Separability of farm and household decisions implies that, when labor productivity in one sector is affected, there is no reason for the other sector to be affected in this case. Any change in labor demand can be met by altering the consumption of leisure and net marketed supply of labor. This is shown in Figure 4 for the case where GTAP elasticities are used and therefore the change in crop labor demand is positive for most households. The figure is an illustration of the relationship that changes in crop labor demand must be compensated for with a combination of changes in non-crop labor demand, leisure consumption, and net marketed supply of labor. That is,

$$\begin{aligned} &Ch.\,in\ Crop\ Labor\ Demand \\ &\qquad = Ch.\,in\ NonCrop\ Labor\ Demand + Ch.\,in\ Lesiure\ Consumption \\ &\qquad + Ch.\,in\ Marketed\ Supply \end{aligned}$$

We see that increased labor demand is met most frequently with large decreases in the consumption of leisure, while marketed supply also adjusts.

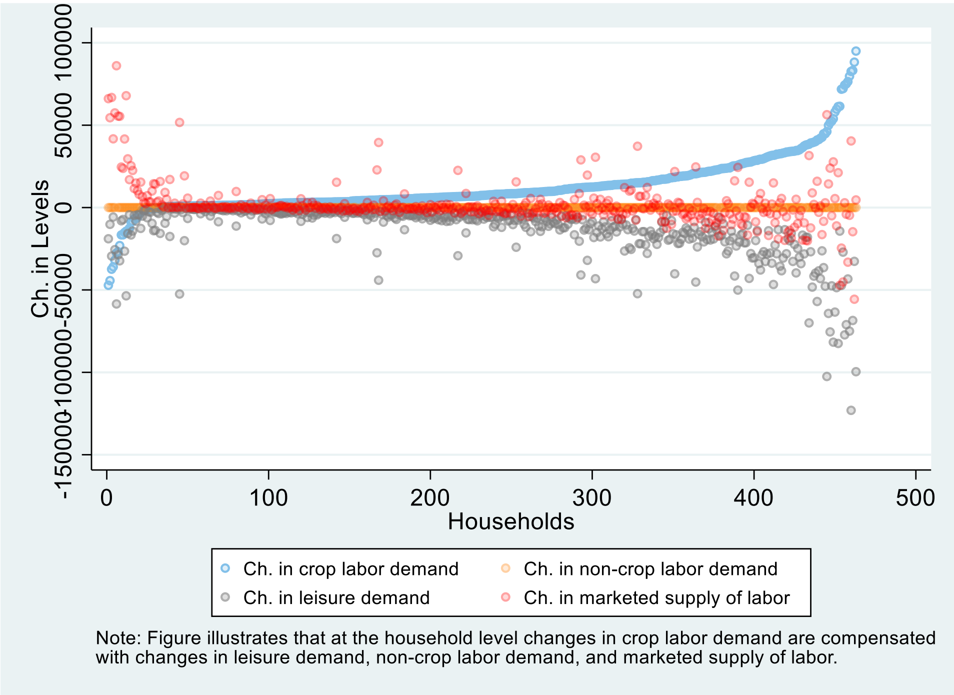

Figure 4: Changes in labor demand for crop, non-crop, leisure, and marketed supply with integrated labor market and GTAP elasticities

Changes in output: Output of crops (the heat stress-affected sector) falls unambiguously regardless of choice of elasticities consistent with analytical Result 2 (see Figure 5). Thus, even when increased labor is drawn into crop production, this is insufficient to prevent a fall in output (when prices and wages are held fixed). The choice of elasticity does however affect the magnitude of the change in crop output. The median decline when the elasticity of substitution in crop production is set to 0.26 (GTAP elasticities) is 2.6% while the median decline is 8.0% when it is set to 0.9 (IFPRI elasticities).

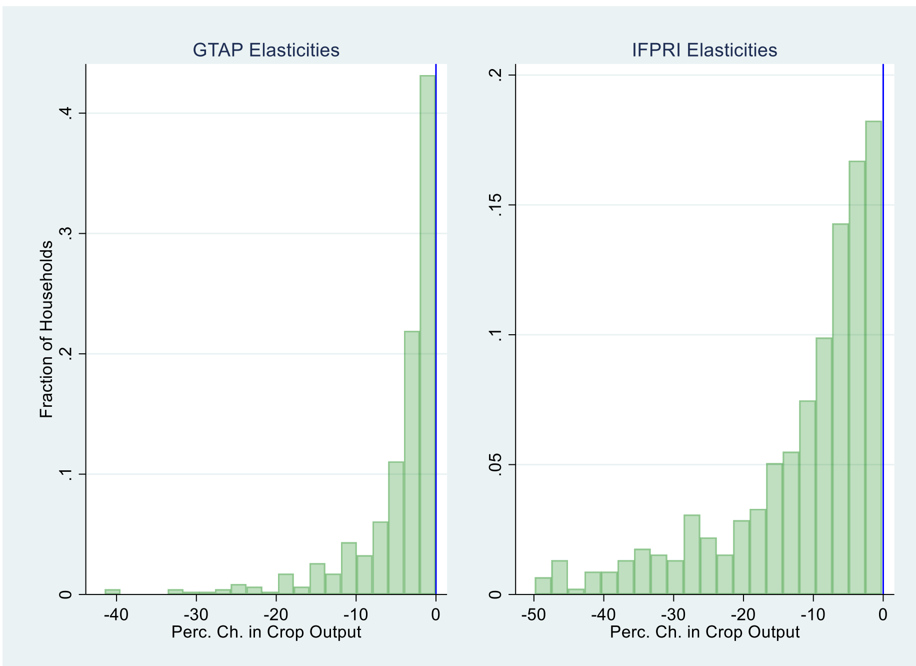

Figure 5: Distribution of percentage changes in output of crops with integrated labor market[8]

Changes in income: In our simulation results, household incomes fall across all households regardless of the value of elasticities. Recall that under Result 3, change in income (all else equal) was theoretically ambiguous. In our sample of households, this ambiguity appears to be resolved in practice and incomes always fall (albeit by larger percentages when the elasticity of substitution in crop production is larger). See Figure 6. This implies that even when labor demand falls in crops due to heat stress (and remains unchanged in non-crops), the fall in output

[8] In the Cobb-Douglas production case, results are similar to the IFPRI case but with larger magnitudes of falls in output.

is larger. (When labor markets are integrated, changes in crop profits are the only source of changes in income).

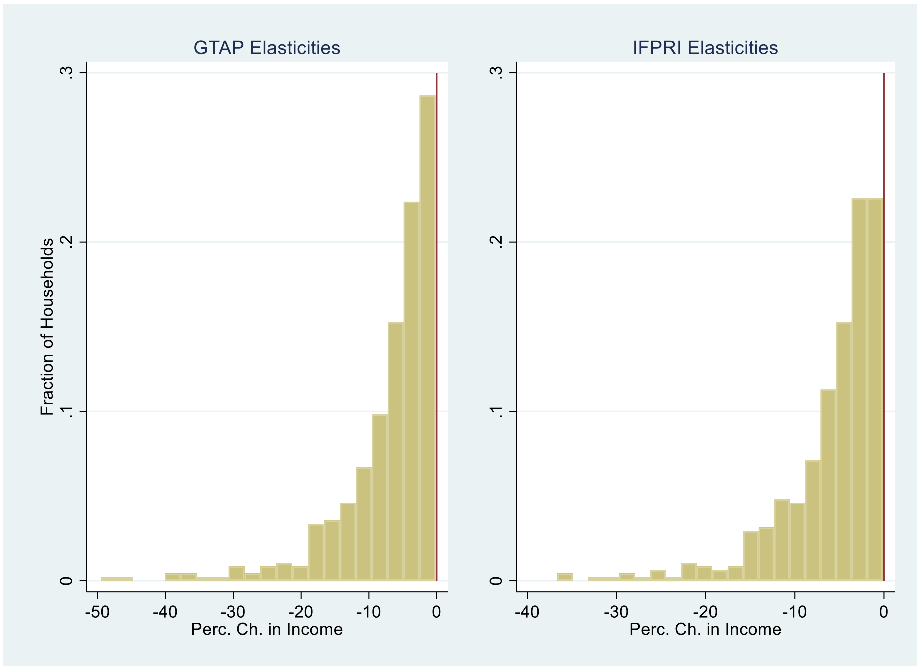

Figure 6: Distribution of percentage changes in income with integrated labor market[9]

Work preferences: Given that incomes fall (unambiguously for all households and under both sets of elasticities), the consumption of leisure also falls given our assumption of Cobb-Douglas preferences over leisure and goods. And a fall in leisure in turn implies an increase in labor supplied to own-production activities, unless a decline in the preference for crop activities were to also occur and was sufficiently large to overturn this. From Result 4, under our theoretical framework, the required decline in preference for crop work is $\hat{\theta}_a < S_R \widehat{Y^*}$. Figure 7 illustrates the distribution of $S_R \widehat{Y^*}$, the minimum required size of the preference shift. In the case where we use GTAP production elasticities, the median decline required is 2.2% (if $\hat{\theta}_a$ declined by 2.2%, half of our sample would supply less family labor to own crop production). In the case where we use IFPRI production elasticities, the median decline required is similar, 2.4%. Thus, fairly modest

[9] In the Cobb-Douglas production case, results are similar to the IFPRI case but with slightly larger magnitudes of falls in output.

changes in preferences would be sufficient to cause households supply less of their own labor to own-crop activities under our framework/treatment of work preferences.

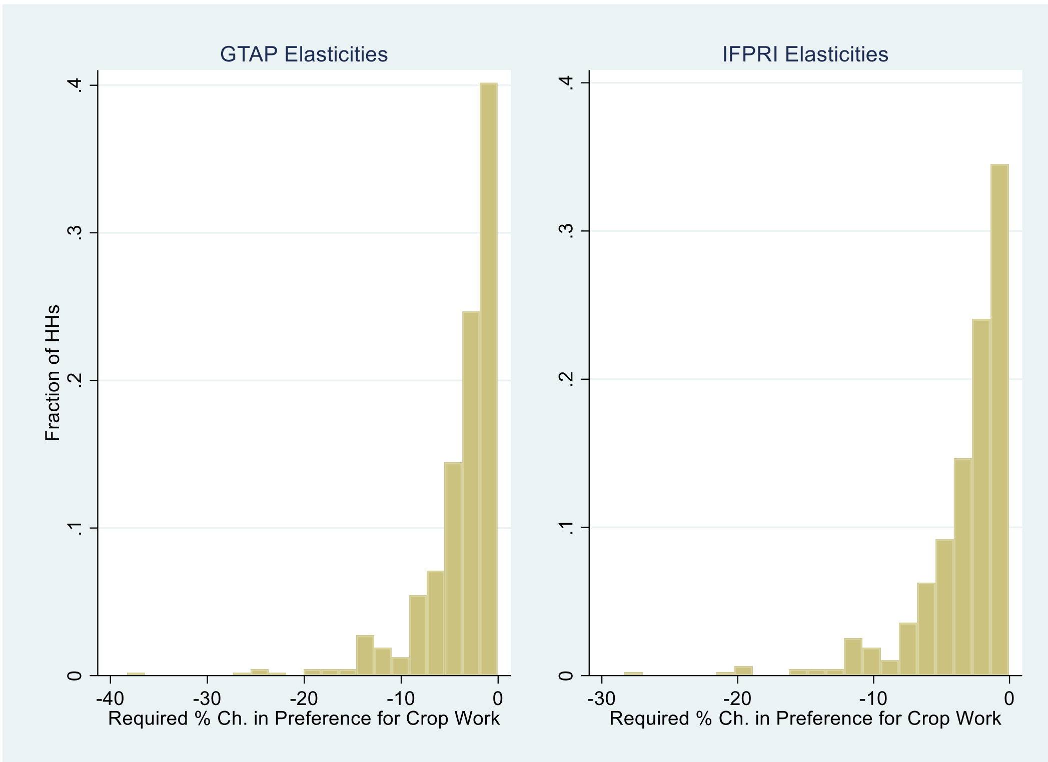

Figure 7: Percentage change in preference for crop work ($\hat{\theta}_a$) required to cause family labor supplied to crops to fall[10]

2.6.3 Solution with segmented labor market

We now turn to the case where labor markets may be constrained. Thus far we have assumed that labor markets are fully integrated allowing households to freely market and hire as much labor as they want. In this section we consider the case where each household's net marketed supply, L^m (where $L^m = L^w - L^h$), is fixed at base levels. Thus, while previous sections address the case where labor markets are entirely unconstrained, this section addresses the other extreme where labor markets are entirely absent.

With this additional constraint, on L^m, and given that we also hold non-labor inputs constants, the separability property fails; households may no longer be able to produce at the profit

[10] In the Cobb-Douglas production case, results are similar to the IFPRI case.

maximizing level when both labor and non-labor inputs are constrained. In this case, with an increase in heat stress and loss of productivity in agriculture, while households may desire to allocate more of their labor to non-crop activities or off-farm market employment, a lack of sufficient employment opportunities and/or labor for hire may mean that family labor is forced to remain in agriculture. That is, it is possible that the household is forced to use more than the profit maximizing level of labor in its home production. Thus, the household, as a producer, is no longer necessarily a profit maximizer; and the separability property fails. We implement this additional constraint in our computable model, and the results under this scenario are as follows.

Labor demand for own production: In the case where labor markets are assumed to be segmented/missing, and the elasticities of substitution are set at the GTAP estimates, household demand for crop labor increases in response to heat stress across most households (93%). See Table 7. As before, this result is reversed to a large degree when IFPRI-based elasticities or Cobb-Douglas elasticities are used instead. With IFPRI elasticities, 63% of households show decreased demand for labor for crop production, while in the Cobb-Douglas case, all 100% of households show decreased crop labor demand. The difference between the integrated and segmented labor markets is that in this case the non-agricultural sector is also affected. Labor is re-allocated between crop and non-crop production. Under GTAP elasticities (low elasticity of substitution in agriculture), when labor demand increases for crops, it decreases for non-crops. Under IFPRI and Cobb-Douglas elasticities, when crop labor demand decreases (for 63% of households), labor demand for non-crop production increases (for all households).

Using GTAP-based elasticities, the median increase in crop labor demand is 14%. If, however, the elasticities of substitution are set at IFPRI-based levels, there is a median decline in crop labor demand of 0.9%, while with Cobb-Douglas elasticities the median decline is -2.7%. So the impact on labor demand in monotonic and declining with a larger elasticity over this range. (The distributions of these results are shown in Figure 8).

Table 7: Demand for labor for own-production activities under segmented labor market

	*HHs with **increased** labor demand*	*HHs with **decreased** labor demand*	***Mean** change in labor demand*	***Median** change in labor demand*
With GTAP-based Elasticities $(\sigma_a = 0.26, \sigma_n = 1.48)$				
Crops	92.3%	7.7%	11.4%	14.0%
Non-crops	17.8%	82.%	-0.7%	-2.5%
With IFPRI-based Elasticities $(\sigma_a = 0.9, \sigma_n = 0.75)$				
Crops	36.6%	63.4%	-3.3%	-0.9%
Non-crops	100%	0%	6.2%	3.6%
With Cobb-Douglas Elasticities $(\sigma_a = 1\ \sigma_n = 1)$				
Crops	0%	100%	-5.4%	-2.7%
Non-crops	100%	0%	8.8%	5.6%

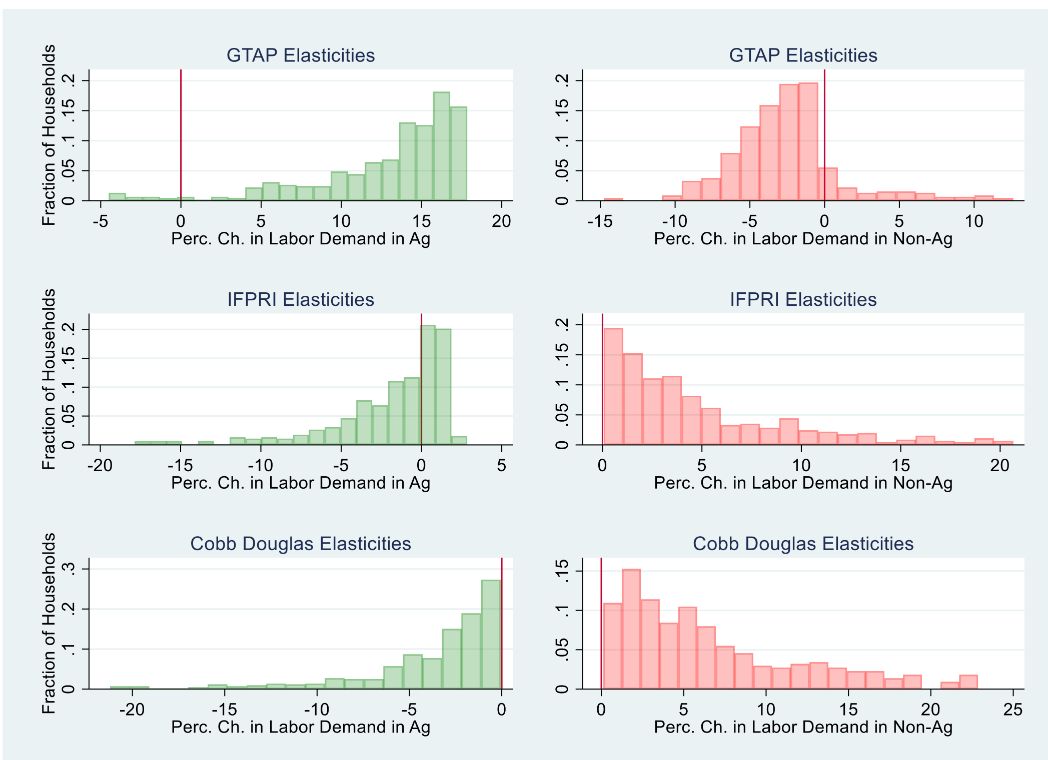

Figure 8: Distribution of percentage changes in demand for labor, by sector and choice of elasticities

In Figure 9, we further illustrate the case where, GTAP-based elasticities are used resulting in increased demand for labor for crop production for most households. Panel A of Figure 9 illustrates how households satisfy this demand increase given the constraints we have imposed on the labor market. The labor market constraint prevents changes in off-farm employment and/or hiring (that is changes in marketed supply are zero in this case). The result is that the increased labor demand is met most frequently by decreasing the consumption of leisure, as in the integrated markets case. However, in this case, a re-allocation from non-crop production activities also occurs. Panel B shows the same result in percentage point terms – the majority of the percentage point increase in agricultural labor demand tends to be met with a re-allocation of leisure. However, it should be noted that this result is sensitive to the level of leisure consumption in the base, and this is not directly captured in the survey and is instead estimated based on assumptions about total labor availability. If our estimation overestimates [underestimates] the level of leisure in the base, the reallocation of labor from non-crop uses would be underestimated [overestimated].

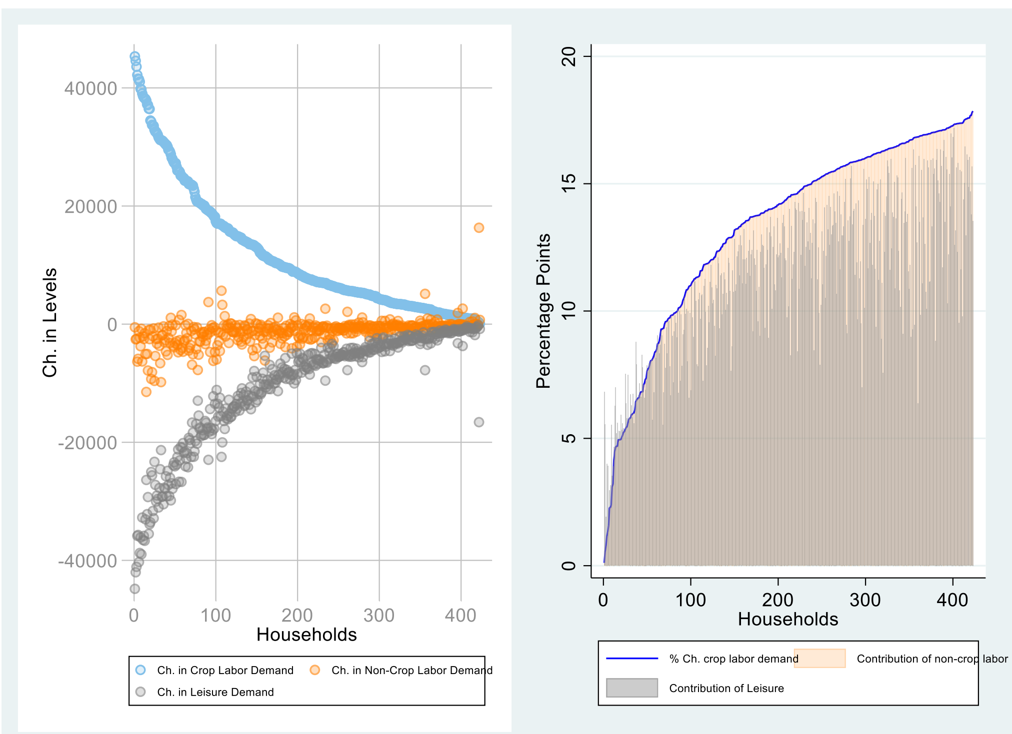

Figure 9: Changes in demand for labor for agriculture, for non-agriculture, and consumption of leisure under model using GTAP-based production elasticities. **Left Panel:** Shows changes in crop labor demand, non-agricultural labor demand, and leisure demand in levels. **Right Panel:** Shows percentage change in crop labor demand, and portions of this percent change met with reductions in non-crop labor demand and leisure

In addition, Figure 10 illustrates the change in (virtual) wages. Recall, that we assume that labor markets are missing and hence there is an endogenous wage rate representing the private valuation of leisure/time. Figure 10 shows that the price (or private valuation) of leisure declines as productivity falls. However, consumption of leisure declines, nonetheless. This is because of falling income which is discussed later.

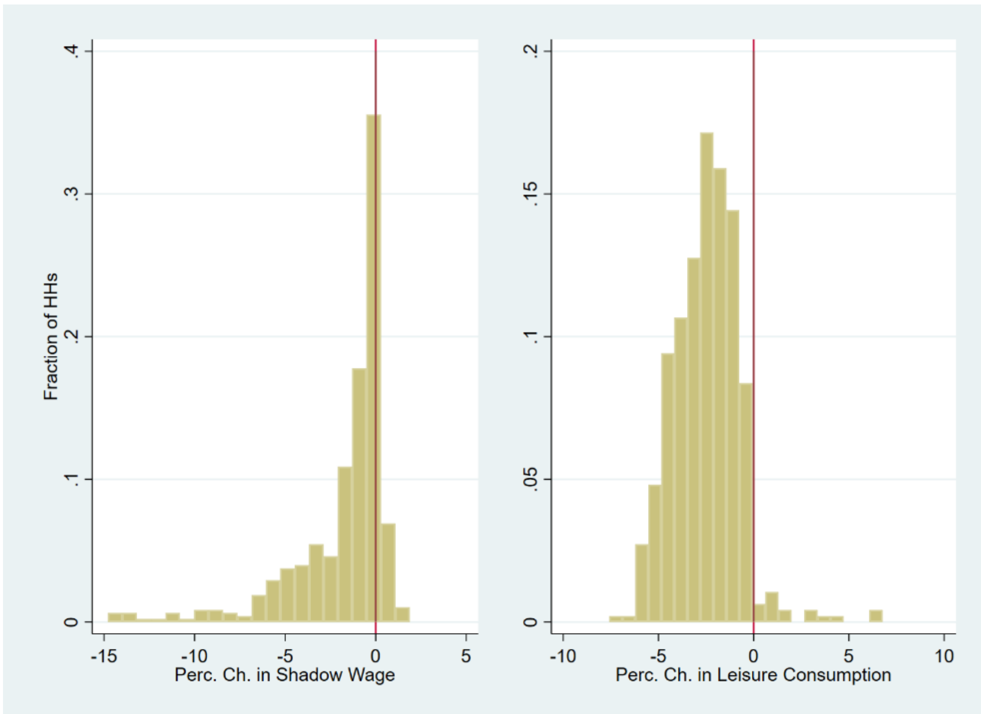

Figure 10: Percentage change in the virtual wage rate/price of leisure, and consumption of leisure, under segmented markets and GTAP elasticities

Turning to the case where we used IFPRI-based production elasticities, resulting in a decrease in labor demand for crop production for over 60% of households, there is not a consistent pattern in how labor and leisure are re-allocated (Figure 11). The freed-up labor (when crop labor demand decreases) is re-allocated to a mix of leisure and non-labor activities. (Those households that have increased crop labor demand tend to meet this by re-allocating leisure as before.)

Changes in the price and consumption are mostly similar under alternative elasticity choices. As before the shadow wage rate falls, while the consumption of leisure falls nonetheless due to falling incomes (shown later).

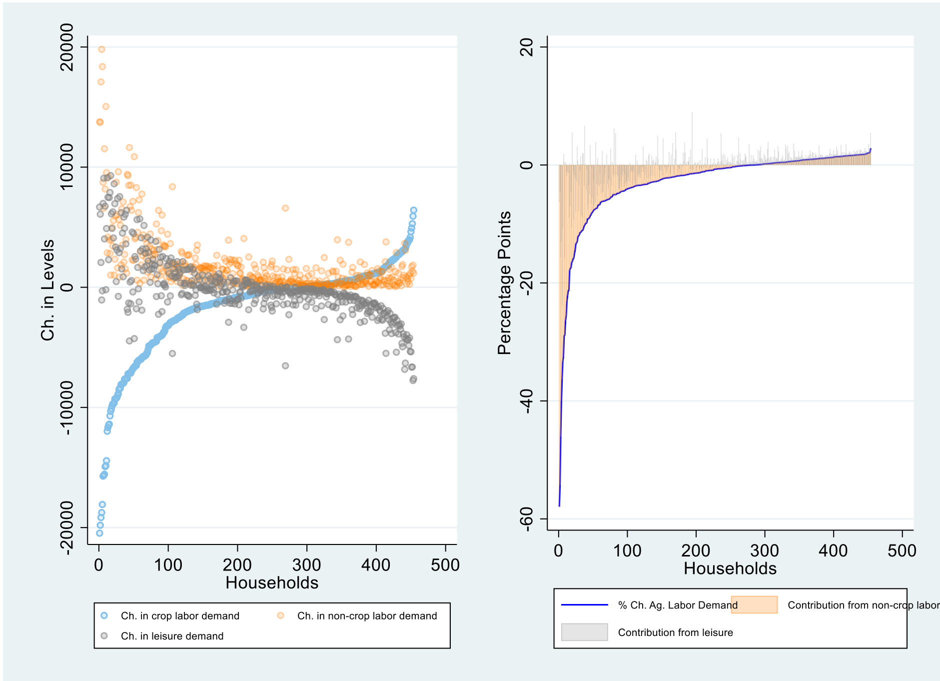

Figure 11: Changes in demand for labor for agriculture, for non-agriculture, and consumption of leisure under segmented labor market and IFPRI-based production elasticities. **Left Panel:** Shows changes in crop labor demand, non-agricultural labor demand, and leisure demand in levels. **Right Panel:** Shows percentage change in crop labor demand, and portions of this percent change met with reductions in non-crop labor demand and leisure

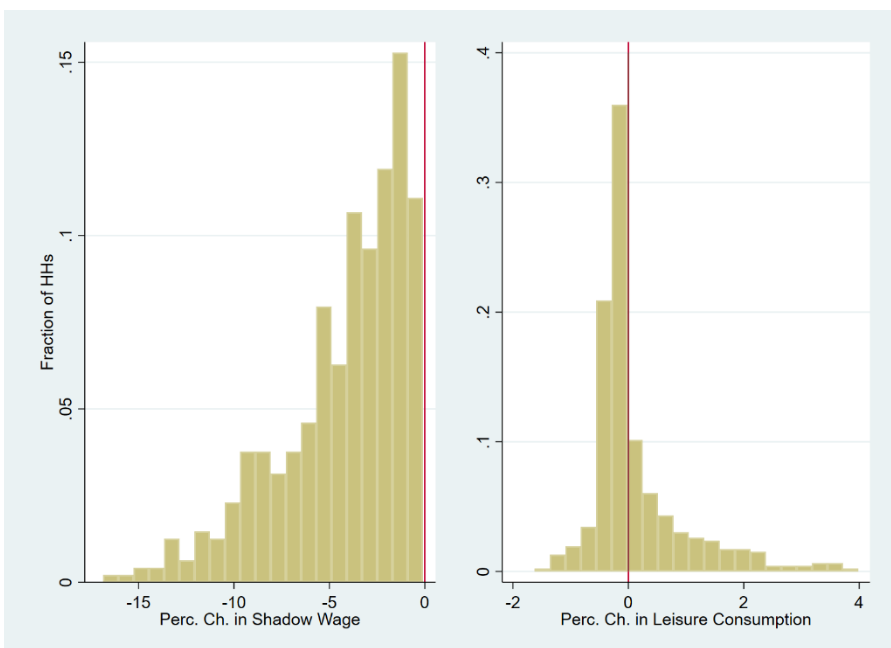

Figure 12: Percentage change in the virtual wage rate/price of leisure, and consumption of leisure, under segmented markets and IFPRI elasticities

Changes in output: The change in crop output is negative across all households regardless of choice of production elasticities (Figure 13). Thus, even with a missing labor market, analytical Result 2, that output of the heat-affected sector falls, holds. However, the magnitudes of these changes are somewhat dependent on the elasticities – with the larger production elasticity in crops (of 0.9 or 1) the median crop output decline is 6.2-6.6% while the median decline is 2.5% when the elasticity is smaller (0.26).

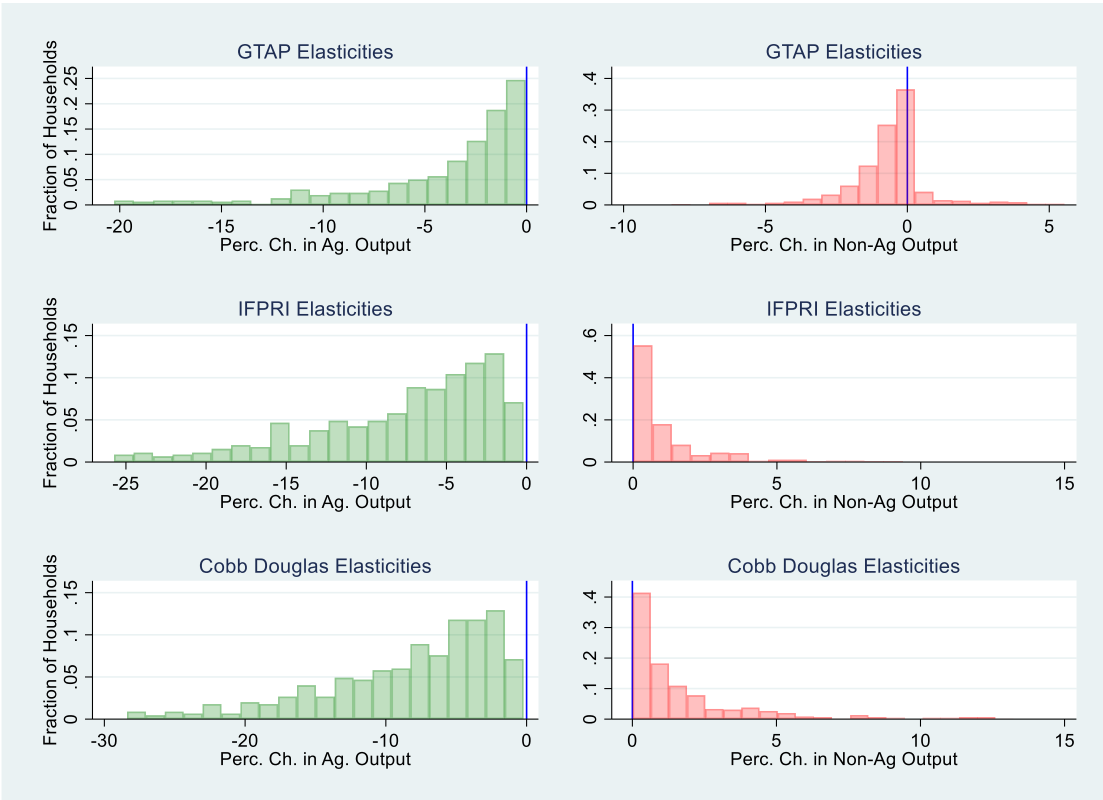

Figure 13: Distribution of percentage changes in production levels, by sector

Change in Income: Median declines in income are similar with GTAP elasticities and with IFPRI elasticities (3.4-3.5%). The distributions of changes in full incomes are shown in Figure 14 while Figure 15 illustrates the decomposition of (full) income changes. In general, declining crop profits drive the income declines. Declines in the value of time (since the private valuation of time changes in this Scenario) plays a role for some households. Profits to non-crop production either increase or remain unchanged. In the case where IFPRI-based elasticities are used, changes in the time and non-crop profit components of full income are sharper but cancel each other to produce overall income results that are similar to those when GTAP elasticities are used.

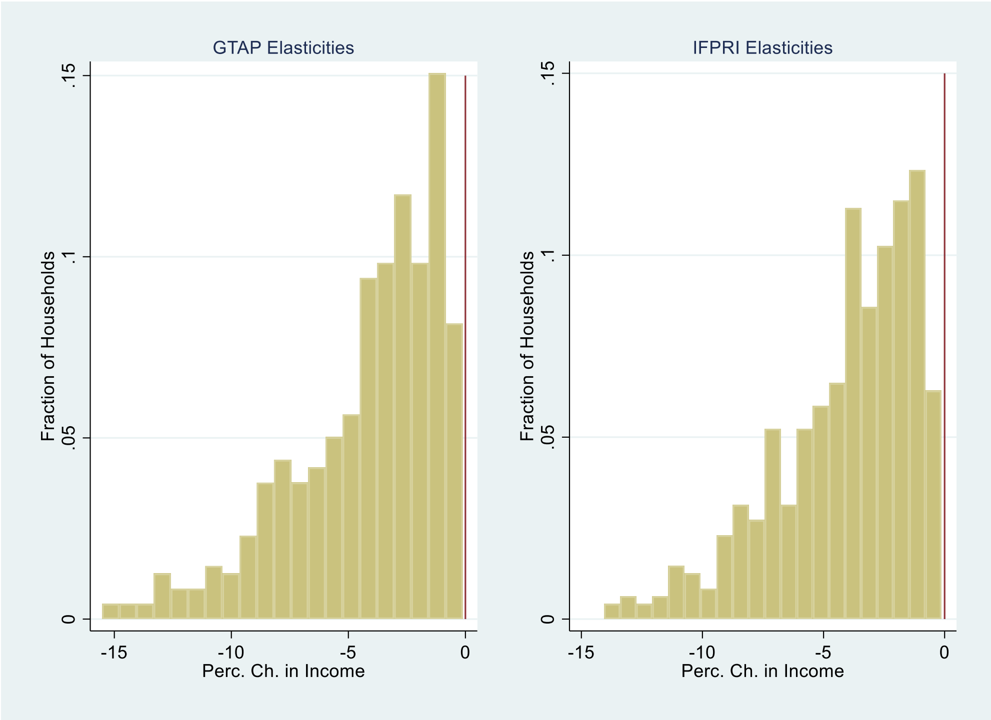

Figure 14: Distribution of percentage changes in household income[11]

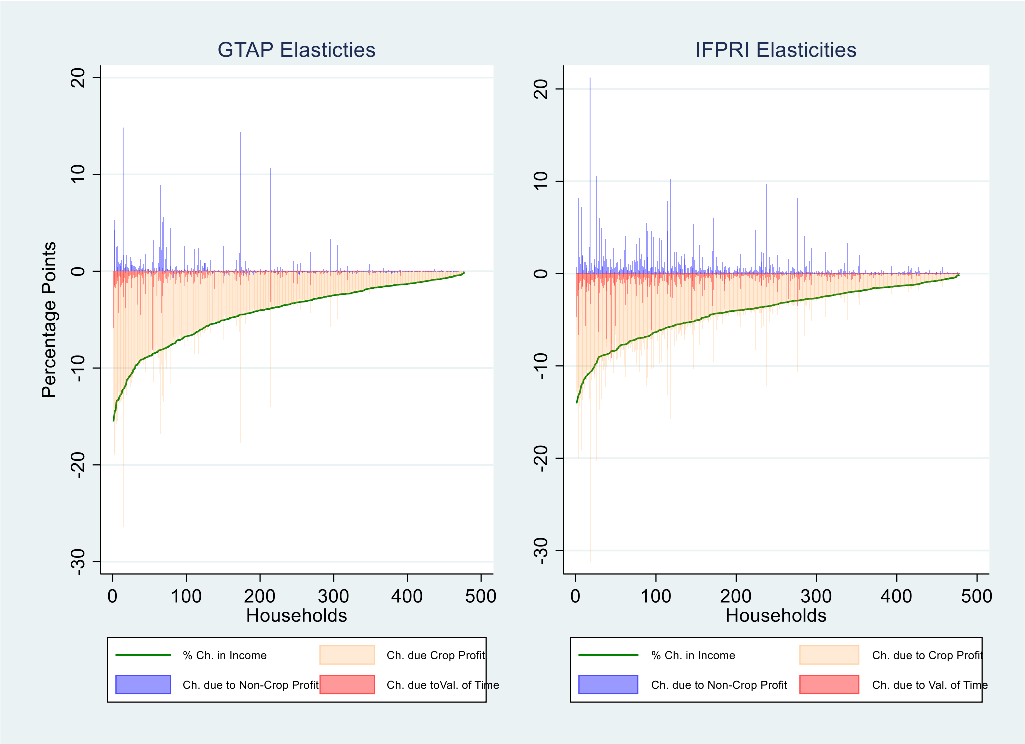

Figure 15: Decomposition of changes in household income

[11] In the Cobb-Douglas production case, results are similar to the IFPRI case.

Work preferences: Similar to the case where the labor market was assumed to be fully integrated, we have the result that incomes fall unambiguously. While the consumption for leisure falls in general, for a small portion of households increases in leisure consumption occur since the (shadow) price of leisure also falls (recall Figure 12). Thus, in this case, we have two sets of households, those with increasing leisure consumption and those with decreasing leisure consumption. Depending on choice of elasticities, of our sample of 480, 3.3-3.6% of households show increasing leisure consumption and hence decreasing labor supplied to production activities. In other words, for these households, heat stress (in labor) and the supply family labor to crops necessarily have a positive relationship.

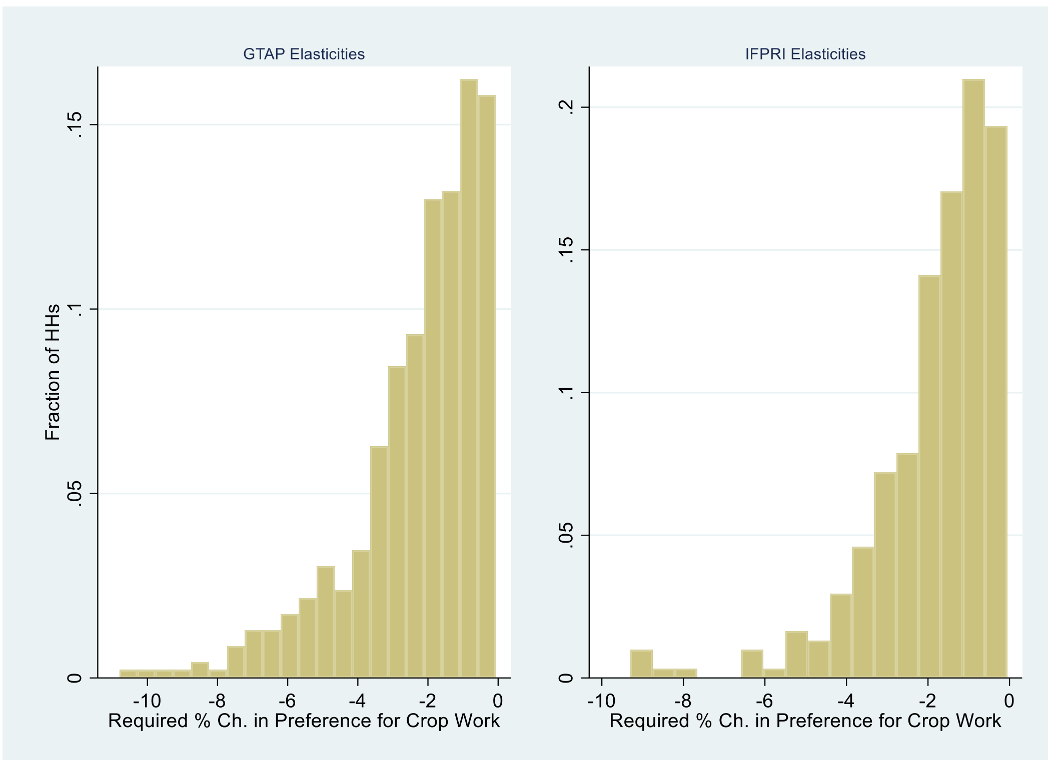

Figure 16: Minimum percentage change in preference for crop work ($\hat{\theta}_a$) required to cause family labor supplied to crops to fall

The majority (96%) of households have decreasing leisure consumption and we can apply a similar analysis as in the integrated labor market case. That is, a fall in leisure implies an increase in labor supplied to both own-production activities, *unless* a decline in the preference for crop work also occurs and is sufficiently large to reverse the relationship. As before, the required decline in preference for crop work is: $\hat{\theta}_a < S_R\widehat{Y^*}$. Figure 16 illustrates the distribution of the minimum required preference shift, $S_R\widehat{Y^*}$, for this second set of households to have a negatively sloped relationship between (family) labor supplied to crop production and heat stress. As before, we find that small changes in preferences would be sufficient to cause family labor supplied to agriculture to decline. In the case where we use GTAP production elasticities, the median decline required is 1.7%. In the case where we use IFPRI production elasticities, the median decline required is 1.4%.

2.7 Discussion

This chapter offers an application of the canonical agricultural household model that allows for the assessment of how agrarian households in low-income economies may respond in terms of their labor allocation choices when affected by heat stress-related labor-productivity losses. This model applies to populations that engage in both the production of crops as well as other goods/services. This description fits significant portions of rural populations in South Asia. In a sample of 2,000 rural households in Pakistan, we find that at least a quarter of households fit this description since the majority of crop farming is done by small-scale farmers who almost always engage in other non-crop production, most frequently small-scale livestock rearing, to supplement their incomes/consumption. For such households, a re-allocation of labor between their cropping and non-cropping activities is an additional margin of response unlike non-producer households (consumer-workers) whose only trade-off is between work (wage employment) and leisure.

Our analysis suggests that at the household level, the first order effect of heat stress-induced labor productivity loss is an increase in labor demand for crop-production (or the more acutely affected household production sector). Strictly monetary incentives would cause this increased demand for labor for crops to be met in large part by decreasing leisure and to a lesser degree with a re-allocation from non-crop production activities. In other words, accounting for only the production side effects of heat stress, our model suggests a positively sloped relationship between family labor supply to crops and heat stress. This contrasts with the finding of (Graff & Neidell, 2014) – who found that American workers tend to increase leisure consumption in response to high temperatures. While the studies are not closely comparable – their study addresses very short-term day-to-day responses whereas our analysis is arguably addressing a more medium-term responses – the contrast is likely indicative of how responses vary across consumer-workers and producer-consumer-workers albeit differences in base-income levels and closeness to poverty may also explain the contrast.

Furthermore, in this study, we also seek to better understand possible shifts in work preferences caused by heat stress. Since preference changes are difficult to measure/observe/identify, past studies only consider the productivity effects of heat stress. In our analysis, we demonstrate that even modest changes in preference could be sufficient to reverse the direction of first-order family labor supply responses caused by the productivity change. Our modelling framework and the analytical results opens the door for identification strategies in future econometric work to estimate preference changes under heat stress. More specifically, under our framework, holding prices, wages, non-labor inputs, total factor productivity (or yield changes) constant, the observed relationship between family labor supplied and heat stress (or heat stress related productivity losses) will be positive *in the absence of preference changes*. In our analysis, this is consistently true for the vast majority of households even under alternative assumptions regarding elasticities of substitution between labor and non-labor inputs as well as alternative assumptions regarding the availability of labor markets and thus separability of the household's problem. Therefore, if instead a *negative* relationship is observed empirically (between heat stress and family labor supplied to the heat stress affected sector), this can be interpreted as being the result of a preference shift. In our simple treatment of preferences for leisure and work, the minimum preference shift that can be assumed to have occurred is then measured by $S_R\hat{Y}^*$. Alternative, specifications of utility could be employed, and the appropriate expression derived in a similar way. We thus illustrate how broad estimates of changes in work preferences could potentially be measured empirically in future works. This will require high quality time-use surveys that are representative of agricultural households in low-income economies. We also note here, that under the assumptions of our model work preferences and labor demand are not directly related. Even in the case where the labor market is assumed to be missing, we have the result that incomes fall across all households, and thus consumption of leisure falls, and more family time is allocated to work. Under our specification of work preferences, changes in these only determine how family worktime is allocated between crop and non-crop activities.

Finally, in our analysis, we considered two different labor market scenarios – in the first we assumed labor markets are unconstrained, whereas the second considers the other extreme where the labor market is entirely missing. Under our model specification, fully integrated labor markets have the advantage of limiting production and farm profit losses only to households' agricultural sector. In the second case, when labor markets are missing, household production even in the non-agricultural sector is affected. These results highlight the benefits of policy responses that bring these low-income households into the labor market, allowing for diversification in earnings.

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CHAPTER 3. THE GENERAL EQUILIBRIUM ECONOMIC IMPACTS OR HEAT STRESS IN LABOR - THE ROLE OF TRADE

3.1 Introduction

In this chapter, we turn to a macro view of the economic consequences of heat stress-induced labor-capacity losses. The focus is on determining the role of trade in mitigating or aggravating national economic welfare losses from labor capacity losses due to heat stress. We know that heat stress will disproportionately affect already hot, humid countries across the tropics. Furthermore, sectors that are labor-intensive and involve substantial outdoor exposure, such as agriculture, construction, and mining, will be disproportionately affected. Thus, hotter countries reliant on labor-intensive, high-exposure sectors are likely to face particularly steep declines in production. However, if high heat stress-affected countries are also net exporters of these heat-stress affected goods, there is potential for some sharing of their welfare losses with net importers via their terms of trade (ToT). For example, if the global production of agricultural commodities falls due to heat stress, their prices will rise relative to other goods. This will benefit countries that are net exporters of these commodities. Conversely, countries that are reliant on imports of heat-stress affected commodities would see a worsening of their ToT and face additional welfare losses. In this way, trade can, in some cases, mitigate heat-stress induced welfare losses, while in other cases trade could exacerbate economic welfare losses.

The extent to which trade can help (or hinder) a heat stress-affected country will depend on, among other features of its economy, what it exports relative to what it imports, how these sectors are affected by heat stress domestically and abroad, and how its trading partners across the globe are simultaneously affected. The broad methodology we employ is comparative static analysis using a general equilibrium (GE) model of the global economy. By using a GE approach, the global nature of heat stress, heterogeneities of its regional impacts, sectoral dependencies, regional trade dependencies, as well as market responses are all accounted for. The model we use is GTAP (Hertel and Tsigas, 1997; Corong et. al., 2007) with a base year of 2014 (Aguiar et. al., 2019). For our experiment, we first estimate heat-stress related labor productivity losses that would occur across the global economy if mean global temperatures were to rise by 3^{o}C. The estimated labor-capacity losses are then introduced as shocks into the general equilibrium model and we assess the resulting impacts on economic welfare and terms of trade relative to the base line.

For our analysis, we focus on nine West African countries/regions. West Africa is among the regions that will be most adversely affected by heat stress-related labor productivity losses under a warmer climate (see Chapter 3). Countries in this region are also highly dependent on agriculture and mining. These sectors constitute large portions of their production but also their exports. Hence, on the one hand their economies will be adversely affected by production losses, but on the other their economic welfare losses could be mitigated by improved terms of trade.

In order to assess the role of trade, we use two complementary methods in our analysis. First, we simulate heat stress-induced labor-capacity losses across the globe and decompose each country's aggregate welfare impact to identify the portion of this welfare change that is caused by terms of trade effects. A country's ToT is a summary statistic that compares its export prices to its import prices. All else equal, an increase in the prices of a country's exports relative to the prices of its imports is welfare enhancing, since their purchasing power in international markets improves. Next, in order to identify what drives the observed ToT effects in each of these nine countries, we decompose their ToT changes into component parts as follows. A country's terms of trade will improve [deteriorate] with (i) increasing [decreasing] world prices of goods which it is a net exporter (ii) increasing [decreasing] prices of its export goods relative to the global average price of these same goods, and (iii) decreasing [increasing] prices of its import goods relative to the global average price of these same goods (McDougall, 2003). This decomposition provides insight into whether an individual country's ToT change and hence trade-induced welfare change is driven by global price changes or rather price changes that are specific to their economy. The former can be interpreted as an indicator that the global-nature of the simulated climate change impact is a significant factor; while the latter is an indicator of the heterogenous nature of heat stress-impacts across sectors and regions, and that country-specific heat stress impacts are important.

A second approach identifies, more explicitly, the extent to which each country's terms of trade changes, and changes in the component parts of its terms of trade, are driven directly by its own heat stress-related productivity losses, and the extent to which these changes are driven by the fact that the rest of the world is also affected by heat stress-related productivity losses. To achieve this, we break down our full experiment into parts in a manner that, in effect, allows us to compare the counterfactual scenario of what would happen if each country were individually affected by heat stress, versus what happens when the rest of the world is also affected.

By using these varied methods, this chapter provides an exhaustive description of how heat stress impacts interact with existing international trade patterns to restrain the negative impacts or amplify them further. Within West Africa, we identify the countries that fall under each category and identify the trade patterns that drive their outcomes. By doing so, we can identify more broadly, the circumstances in which, or the economic features, that would allow a country to see beneficial trade-induced welfare impacts in a world where labor is affected by increasing heat stress.

3.2 Related literature

This chapter builds upon a growing number of studies that address the global economic impacts of climate change-induced labor capacity losses. As has been previously noted, a number of scientific studies provide increasingly improved approaches for measuring and projecting future heat stress, as well as estimates of the potential loss of (manual) labor capacity that would result (see for example, Kjellstrom et. al. 2009; Bröde et. al., 2018; Kjellstrom et. al. 2018; Buzan & Huber, 2020; Kong & Huber, 2021;). These studies project heat stress levels in the future will result in substantial losses of labor capacity in regions such as the Middle East, parts of Africa, South Asia, and Southeast Asia, where increasingly high temperatures will coincide with high humidity under a warming climate.

Second, a growing body of economic studies assess the extent to which these losses in labor capacity will lead to economic losses and distributional consequences across the globe considering market responses, and global sectoral and trade dependencies (de Lima et. al., 2021; Orlov et. al., 2020). These existing studies have made contributions towards identifying those regions that are most vulnerable to economic losses and demonstrating that labor capacity losses are a non-trivial aspect of global warming. The role of international trade in determining economic welfare across the globe, however, has only been addressed tangentially in these studies. The contribution of this study lies in its focus on international trade and elaborating the role it may play in mitigating or exacerbating economic losses across countries. As such, the publications that are most closely relevant to this study are Knittel et. al. (2022), Gouel & Laborde (2021), and Randhir & Hertel (1999). These studies are described at greater length below.

Knittel et. al, (2022), like this paper, are concerned with labor capacity losses, their general equilibrium consequences, and the role of international trade. Their specific focus, however, is on the German economy. They find that, while Germany is not directly affected by significant heat stress, its trade balance and the regional and sectoral composition of its trade is nonetheless impacted, given its strong reliance on international trade. They find that the country's trade balance improves, and this is driven in large part by labor productivity declines in the rest of the world, outside of Europe. In contrast, this chapter focuses on nine West African countries, and offers analysis that highlights how heat stress impacts are transmitted via trade and allows for more generalizable conclusions.

The studies by Gouel & Laborde (2021) and Randhir and Hertel (1999) on the other hand, focus on crop yields rather than labor capacity losses. However, their methods inform the approaches we take in our analysis. The issue addressed by Gouel & Laborde (2021) is that the negative yield impacts of climate change disproportionately affect countries in and around the tropics, while countries at higher latitudes could experience yield gains as temperatures rise. Thus, trade and production shifts can mitigate global economic welfare losses. Relatedly, Randhir and Hertel (1999) consider the extent to which trade liberalization could mitigate the economic consequences of crop yield losses. Both studies use counterfactual scenarios, where trade responses are restricted in order to isolate the impact of trade. Randhir and Hertel (1999) additionally also use a welfare decomposition to separate out the welfare effects related to tariff and subsidy policies. Their methods are discussed in more detail in the following section, since our study follows their approaches.

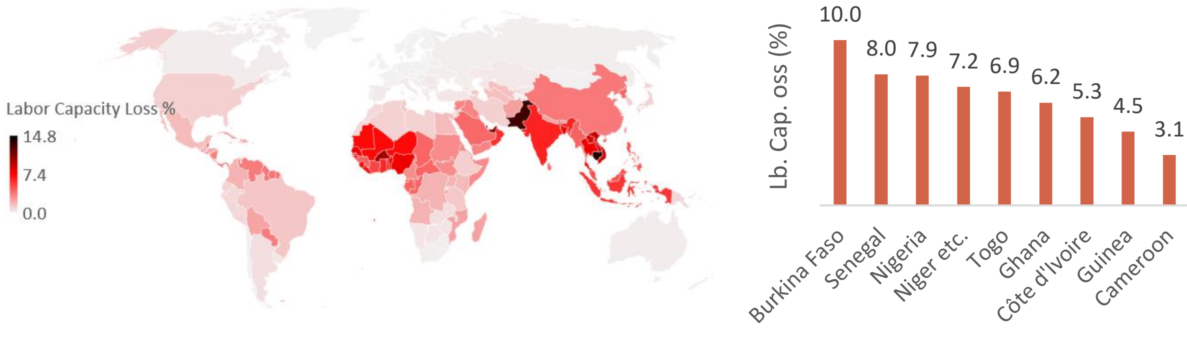
3.3 Methods and data

3.3.1 Overview of methods

Broadly, this study uses comparative static analysis in the context of a global general equilibrium model. We use the standard GTAP model – a general equilibrium model of the global economy (Hertel and Tsiagas, 1997; Corong et. al. 2017). In our application of the GTAP model, the global economy is disaggregated into 137 regions/countries and 65 sectors using version 10 of the GTAP database (Aguiar et. al., 2019). In general, we use default GTAP parameter specifications, with the following exceptions/extensions. While the analysis reported in this Chapter focuses on results obtained default GTAP Armington trade elasticities, we also considered an alternative specification where these elasticities were doubled. This is considering Brown (1987), who finds that the Armington-based models yield strong terms-of-trade effects due to implied monopoly power under Armington assumptions. By considering larger elasticities, this monopoly power is reduced, and we assess the degree to which our conclusions are sensitive to this.

Furthermore, we also divert from standard GTAP assumptions with regards to labor mobility. Following Keeney and Hertel (2005), we assume segmentation in the market of labor such that labor is not perfectly mobile across agricultural and non-agricultural sectors. That is, we assume that agricultural labor cannot seamlessly transfer from agricultural to manufacturing and services, and vice versa. Finally, with regards to input substitution elasticities, we employ standard GTAP elasticities for this analysis. We however note here the limitation that, in light of our findings in Chapter 2, input substitution elasticities are potentially important in determining factor employment and hence output and price outcomes.

Within the model as described above, we introduce labor productivity losses that we project would occur if mean global temperatures were to rise by 3^{o}C, relative to the period 1961-1990. The methods used to obtain our projections of future heat stress and the resulting loss of labor capacity/labor productivity are described at length in Chapter 4. We only mention here briefly that our estimates of labor capacity losses are based on climate data projections from 13 different climate models and heat stress is measured using the Wet Bulb Globe Temperature (WBGT). The WBGT is a metric that accounts for all factors that affect the human body: temperature, humidity, wind conditions, and solar radiation. For our study, the WBGT is estimated using more precise methods than past studies and furthermore, unlike past studies, we account for varying intensities of work performed at varying frequencies in different sectors. Projection of labor capacity losses, given WBGT projections, are then assessed the labor response function of Bröde et. al., 2018 and assuming work-rest cycles that follow ISO safety standards. The resulting estimates of labor capacity losses using these approaches, aggregated to the regional level are shown in Figure 17. We find that the largest labor capacity losses occur in the Middle East and South Asia (11-15%). In West Africa, labor capacity losses generally range from 5-10% with the exception of Cameroon and Guinea, which experience lower losses.



A. World B. West Africa

Figure 17: Country-level labor capacity losses (%)

Within this broad approach/framework, identifying the role of trade can be achieved in several ways. Knittel et. al. (2022) use the straightforward approach of simulating labor capacity losses (under alternative global warming scenarios) and comparing trade outcomes for Germany under this scenario against the baseline (i.e. a scenario of no climate change). Gouel and Laborde (2021) and Randhir and Hertel (1999), on the other hand, use a counterfactual of "restricted trade" to identify the role of trade in response to climate-induced crop yield shocks. Comparing outcomes under these two alternatives provides a measure of the extent and direction of the role of trade. A "restricted trade" scenario however is not straightforward to define. Gouel and Laborde (2021), consider two alternative trade response restrictions. The first holds bilateral export shares fixed, that is, countries cannot adjust their export destinations in response to the climate-induced yield shock. The second holds import shares fixed – i.e., countries cannot adjust their import sources. Randhir and Hertel (1999) on the other hand, restrict import demand responses by disrupting the transmission of price changes from the international market into domestic markets. Furthermore, Randhir and Hertel (1999) also employ methods to decompose welfare changes into informative component parts (using the methods of Huff and Hertel, 2001).

For this study, we use the following methods. Like Knittel et. al. (2022), we take the approach of simulating labor productivity losses and compare outcomes relative to the baseline. However, we isolate the role of trade by assessing country-level welfare losses, and then use the welfare decomposition method of Huff and Hertel (2001) to determine the portion of the welfare loss, in each country, that can be attributed to terms of trade effects. The welfare decomposition method is described further under Section 3.3.2. We are, however, also concerned with delineating the specific causes of ToT changes in order to explain why, when labor is affected by heat stress globally, some countries benefit from terms of trade improvements (and see their aggregate welfare losses mitigated), while others are further harmed by deteriorating terms of trade. To do this, we focus on a sample of West African countries, and decompose their terms of trade changes into component parts that aid this analysis. A country's terms of trade are the net outcome of (i) global price changes of goods that it trades in, and (ii) changes in the prices of its specific exports and imports relative to world prices. Section 3.3.3 details these components more formally. By decomposing each country's ToT in this way, we begin to identify the countries that tend to be affected more by global changes than their own region-specific factors, and by analyzing the composition of their trade we explore why.

Next, we use a second approach to identify more explicitly the extent to which each country is affected by its own heat stress and the extent to which it is affected by heat stress abroad. In theory, international trade allows for economies to be affected even if they themselves were unaffected by heat stress directly. In other words, when heat stress affects labor across the globe simultaneously, but heterogeneously, countries are impacted first because they themselves are experiencing heat stress, but they are also impacted further because other countries (with whom they trade with and/or compete with in the international market) are affected by heat stress. We therefore decompose individual country's terms of trade effects into these two channels explicitly by using "subtotals" of our experiments/implemented shocks (Harrison et. al. 2000). This method is akin to using a counterfactual approach: comparing outcomes when an individual economy is affected by heat stress-induced labor-capacity losses alone versus outcomes when other economies are also affected simultaneously. Using this approach, we identify, for each individual West African country, the change in its welfare and ToT that are due to (i) heat stress in the individual country itself, (ii) heat stress in the rest of West Africa, and (iii) heat stress in the rest of the world. This method is described further under Section 3.3.4.

3.3.2 Welfare decomposition

A complete discussion of the welfare decomposition method used in this paper is provided by Huff and Hertel (2001) and summarized here briefly for completeness. The GTAP model assumes a utility maximizing representative household for each region. The regional household derives utility from private, government, and savings expenditures; and changes in the regional household's utility (in response to a shock) provides a measure of how much economic welfare is affected. More specifically, in GTAP changes in regional welfare are measured by equivalent variation – the expenditure required to obtain the new (post-simulation) level of utility at baseline prices.

This change in welfare, measured by equivalent variation, can be decomposed into component parts that attribute the welfare change to specific causes. In the case of the labor productivity changes that we implement for this analysis, changes in welfare will arise due to technological effects (the direct effect of the heat-stress induced productivity change itself), changes in allocative efficiency, and due to terms of trade effects. These effects are described in intuitive terms as follows while more formalized treatments can be found in Huff and Hertel (2001) as well as Randhir and Hertel (1999).

Intuitively, "technological effects", in our experiment, measures the welfare loss caused directly by the loss of productivity: that existing resources (labor) are now able to produce less. The loss of labor productivity then results in re-allocations of labor, changes in production across sectors, as well as changes in consumption, volumes of exports and imports. These volume shifts give rise to "allocative efficiency effects". These are welfare changes that arise when quantity/volume changes interact with pre-existing taxes and subsidies. Welfare gains [losses] result if a shock pushes a taxed or subsidized quantity closer to [farther from] what would be optimal in the absence of the pre-existing tax or subsidy. For example, if the heat stress shock caused volumes of imports of a certain good in a region to increase which were previously depressed by pre-existing tariffs, the heat stress shock would be welfare-improving for the region in this aspect because it counteracts the effects of the tariff. Finally, the experiment considered in this paper will give rise to changes in the terms-of-trade. The "terms of trade effect" summarizes the welfare effects of a region's export prices changing relative to its import prices. When export prices rise relative to import prices, the regional household's welfare is improved as, all else equal, greater import consumption is possible with the same quantities of exports sales.

3.3.3 Terms-of-trade decomposition

As noted earlier, an individual countries ToT is a summary statistic that considers (i) global prices o f a country's internationally traded goods, (ii) the specific prices of a country's export goods relative to the global average price of those goods, and (iii) the specific prices of a country's import goods relative to the global average prices of those goods. Thus, the percentage change in a country r's terms of trade (tot_r), can considered to be comprised of these three components (McDougall, 2003):

$$tot_r = c1_{i,r} + c2_{i,r} - c3_{i,r} \tag{26}$$

where each component is defined as follows.

The first component, $c1_{i,r}$ s the contribution of the world export price of good i to the ToT change of region r, and is given by:

$$c1_{i,r} = \left(SX_{i,r} - SM_{i,r}\right) * (px_i - px) \tag{27}$$

where $SX_{i,r}$ and $SM_{i,r}$ are the shares of good i in region r's baseline exports and imports respectively; px_i is the percentage change in the global average export price of good i; and px is the percentage change in the global price index of all goods. A country that is a net exporter of good i (that is, $SX_{i,r} - SM_{i,r} > 0$) will therefore experience a ToT improvement driven by this component, $c1_{i,r}$, if the global price of i rises relative to other goods ($px_i - px > 0$).

The second component, $c2_{ir}$, is the contribution of the regional export price of good i to the ToT change of region r, and is given by:

$$c2_{ir} = SX_{i,r} * \left[px_{i,r} - px_i\right] \tag{28}$$

where $SX_{i,r}$ is the shares of good i in region r's baseline exports as before; and $px_{i,r}$ is the percentage change in region r's export price of good i. A country r that is an exporter of good i (i.e., $SX_{i,r} > 0$) will therefore experience a ToT improvement driven by this component, $c2_{i,r}$, if its export price of i rises relative to the world price of i (i.e., if $px_{i,r} - px_i > 0$).

The final component, $c3_{i,r}$, is the contribution of the regional import price of good i to the ToT change of region r, and is given by:

$$c3_{i,r} = SM_{i,r} * \left[pm_{i,r} - px_i\right] \tag{29}$$

where $SM_{i,r}$ is the shares of good i in region r's baseline imports as before; and $pm_{i,r}$ is the percentage change in region r's import price of good i. A country that is a an importer of good i ($SX_{i,r} > 0$) will therefore experience a ToT deterioration driven by this component, $c3_{i,r}$, if its import price of i rises relative to the world price of i (i.e., if $pm_{ir} - px_i > 0$).

3.3.4 The "subtotals" approach

Harrison et. al. (2000) identify that in any GE experiment that is composed of shocks to multiple exogenous variables, we can decompose the resulting change in any endogenous variable of interest into contributions made by the change in each exogenous variable. In other words, the results of any experiment in a GE model, that is comprised of multiple shocks, can be broken down to "subtotals" of that experiment that identify the role of the shocks separately. The advantage of their approach is that the subtotals are guaranteed to sum to the total impact. This would not be the case if the experiments were conducted separately (due to interaction effects).

In our case, the exogenous variables shocked are the productivities of each labor type, in each region, and in each sector; the endogenous outcome variable we focus on is the terms of trade; and the decomposition that we consider, that is useful in identifying the role of trade, is as follows. For each of the nine West African countries in our analysis, we decompose the portion of their terms of trade change caused by its own productivity shock. That is, the first "subtotal" – which we label "own effects" – considers the impact of the labor productivity shocks implemented for that country alone. For example, the "own effects" for Ghana, will measure how the terms of trade of Ghana are impacted by the shocks originating in Ghana. The next "subtotal" considers the impacts stemming from labor capacity losses in all other West African countries. We refer to this component as "Rest of West Africa effects". The final subtotal labelled "Rest of world effects" considers the impact of labor productivity shocks in those countries excluding the nine West Africa. The Harrison et. al. (2000) method ensures that the subtotals sum to reproduce the outcome of the full experiment. That is, the terms of trade change in a given region is the sum of "own effects", "rest of West Africa effects" and "rest of world effects". Furthermore, the change in each sub-component of each region's ToT change (i.e., $c1_{ir}$, $c2_{ir}$, and $c3_{ir}$), can also be decomposed into changes driven by "own effects", "rest of West Africa effects" and "rest of world effects".

3.4 Results

3.4.1 Trade patterns in West Africa in the base

Given our focus on West Africa, it is informative to begin with a description of existing trade patterns in the region. Figure 18 illustrates the composition of trade in these countries – what they export (Panel A) and what they import (Panel B) – in terms of broad categories of goods. We see that these countries are fairly similar in terms of what they import but their exports vary. Cote d'Ivoire stands out from the rest of West Africa in terms of its exports. More than 40% of its exports are of agricultural goods (and a further 20% are processed foods). Unlike, the other countries considered, its export share of mining and closely related manufactured mineral and metal goods is low. The remaining eight countries can be divided into two groups: Ghana, Togo, Cameroon and Burkina Faso each have an agricultural export share of at least 15%. For the rest (Nigeria, Guinea, Senegal, and "Niger etc." which is an aggregate of all other West African countries), this share lies in the single digits. It is also useful to take note of these countries' export shares of "extractive industries" which includes all mining, petroleum, non-metallic mineral, non-ferrous metals, and iron and steel products. For Guinea and Nigeria this share is especially large, and also substantial for Burkina Faso, Ghana, and the rest of West Africa region aggregate.

Figure 19 shows the regions these countries export to and import from. Panel A shows that the bulk of West Africa's exports go to the rest of the world, outside of West Africa.

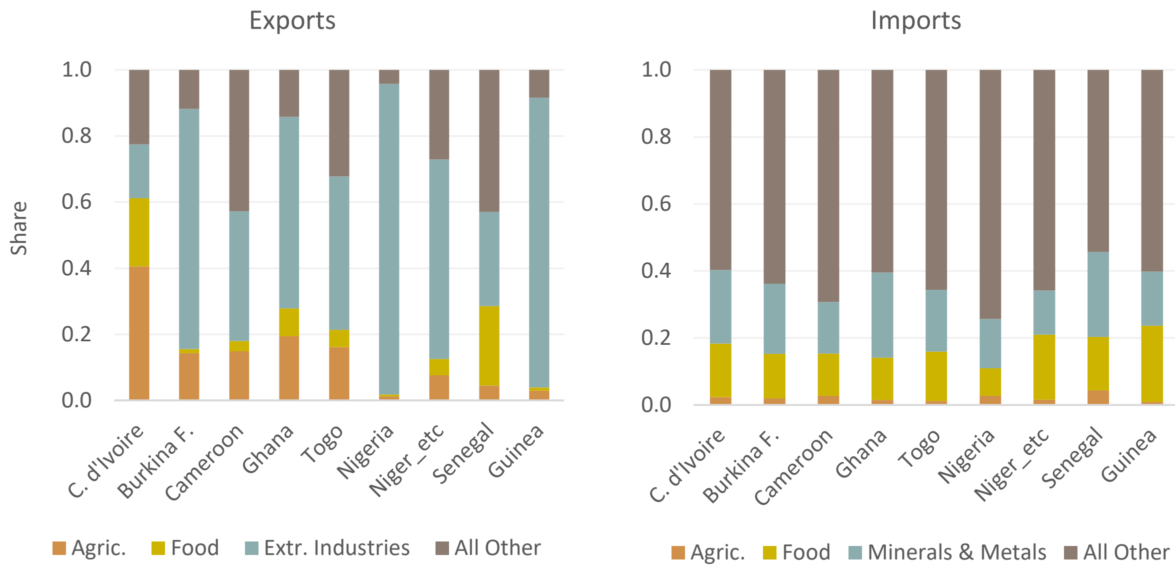


Figure 18: Export and import shares of major commodity groups, by country

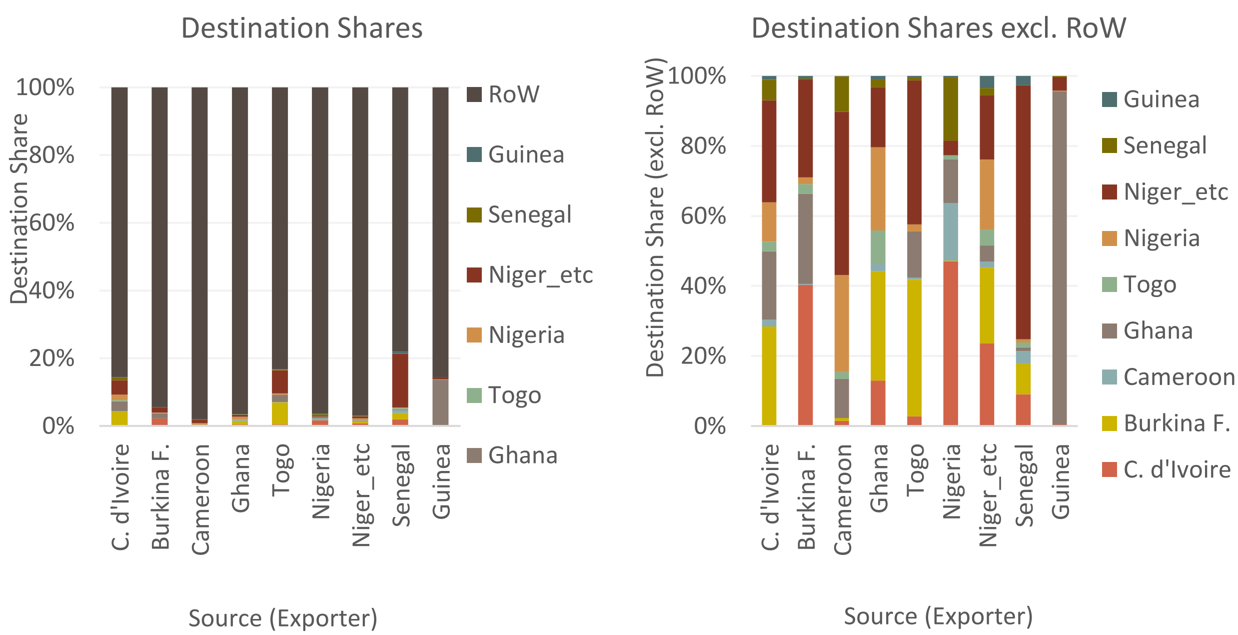


Figure 19: Destination shares of total exports, by source country

3.4.2 Welfare and terms-of-trade impacts across the world

Turning to the results from our experiment, we begin with a global, macro view of the impacts of heat-stress induced labor capacity losses. Figure 20 shows changes in economic welfare across the globe. Except for countries/regions that lie close to the poles, most of the world's economies see welfare declines with the largest welfare losses (in percentage terms) concentrated in regions closer to the tropics. This includes West Africa.

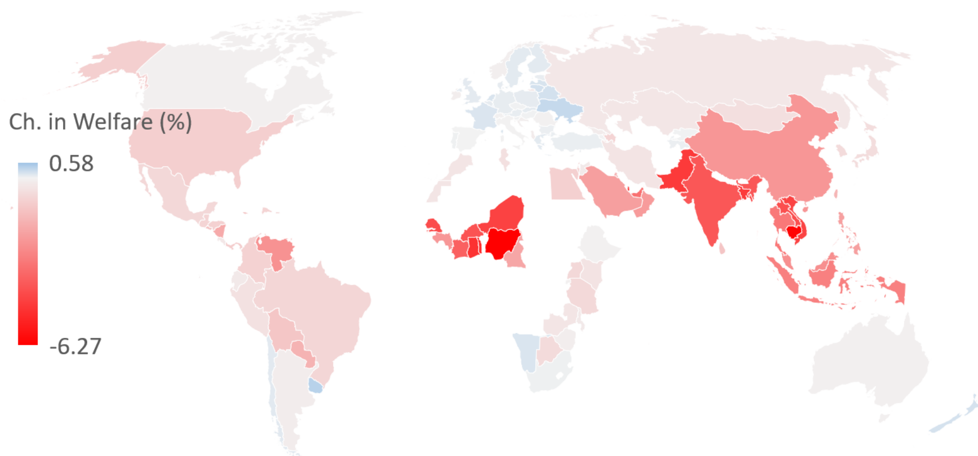


Figure 20: Percentage change in welfare.

Note: Percentage change in welfare is equal equivalent variation as a percentage of household income in the base. Map excludes regions that fall under GTAP "Rest of" region aggregates. Value for "Rest of West Africa" has been assigned entirely to Niger in this chart. The value for Niger therefore also includes welfare losses of: Benin, Cape Verde, Gambia, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Saint Helena, and Sierra Leone.

Using the methods Huff and Hertel (2011), the welfare losses/changes in Figure 20 can be decomposed into component parts as described previously in Section 3.3.2. Across most countries, the majority of the loss of welfare can be attributed to "technological effects" – that is, they are the direct consequence of the simulated labor productivity loss: a loss of labor productivity reduces welfare as more resources must be used to produce the same level of output. In addition to this are welfare changes that result from indirect channels. Economic welfare changes due to "allocative effects" – as labor productivity changes, factors of production are re-allocated across sectors. This can move an economy closer or farther from what is optimal depending on how these re-allocations interact with existing taxes and subsidies.

Our focus here lies with the third component/cause of welfare changes: “terms of trade effects”. As labor productivity losses impact countries and sectors heterogeneously, relative prices of goods change across sector and regions change. Sectors that are disproportionately affected will see commodity prices increase globally. Economies that are disproportionately affected will also see their specific regional prices increase in excess of the average global increase. As described under the methods section, countries that are net-exporters of heat stress-affected commodities, can see a silver lining in a warming world: improved terms of trade. Figure 21 illustrates the welfare effects due to terms of trade changes across the globe

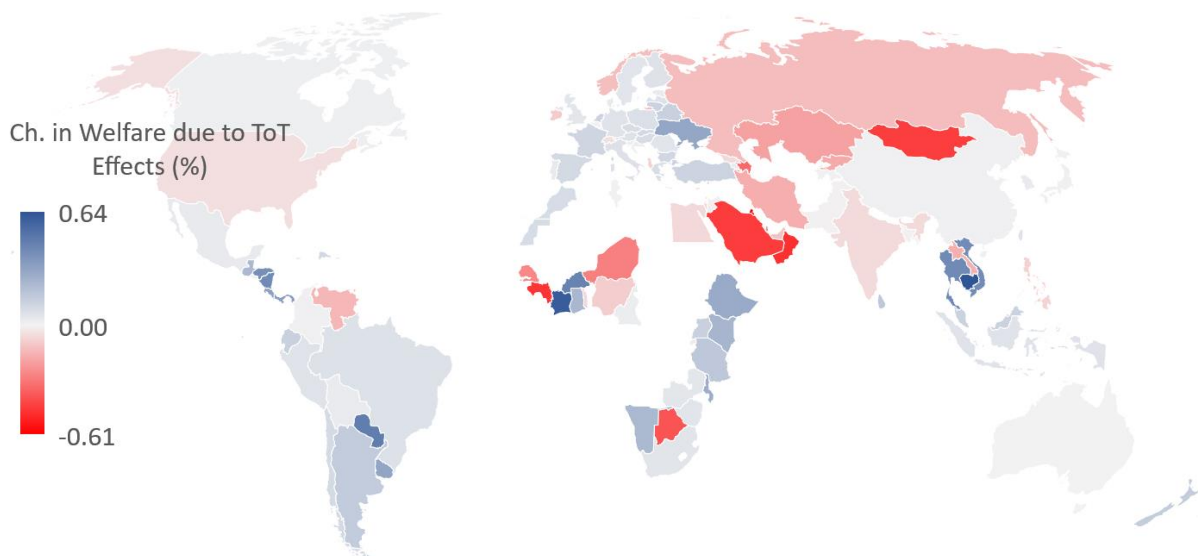


Figure 21: Changes in welfare due to terms of trade effects (p.p.).

Note: Map generally excludes regions that fall under GTAP “Rest of” region aggregates. Value for “Rest of Africa” has been assigned entirely to Niger in this map. Thus, the value for Niger also includes welfare losses of: Benin, Cape Verde, Gambia, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Saint Helena, and Sierra Leone.’

In contrast to welfare changes as a whole (shown in Figure 20), ToT-related welfare changes in Figure 21 are heterogenous in sign. Southeast Asia, Latin America, East Africa have positive ToT-related welfare changes, while within West Africa both ToT-related gains and losses occur.[12] This variation in trade effects within West African countries is the focus of the remainder of our analysis.

3.4.3 Terms-of-trade impacts in West Africa

Our region of interest, West Africa, is split between countries that see ToT-related welfare increases (mitigating their overall welfare loss) and countries that see ToT-related welfare decreases (i.e., their welfare loss is aggravated further by trade). Figure 22 illustrates the decomposition of welfare changes in the West African countries. It shows that Cote d'Ivoire, Burkina Faso, Cameroon, Ghana, and Togo see positive ToT-related welfare effects. Negative ToT-effects on welfare occur in Guinea, Senegal, Nigeria, and "Niger etc." (which is an aggregate that includes all other West African countries such as Niger and Benin).

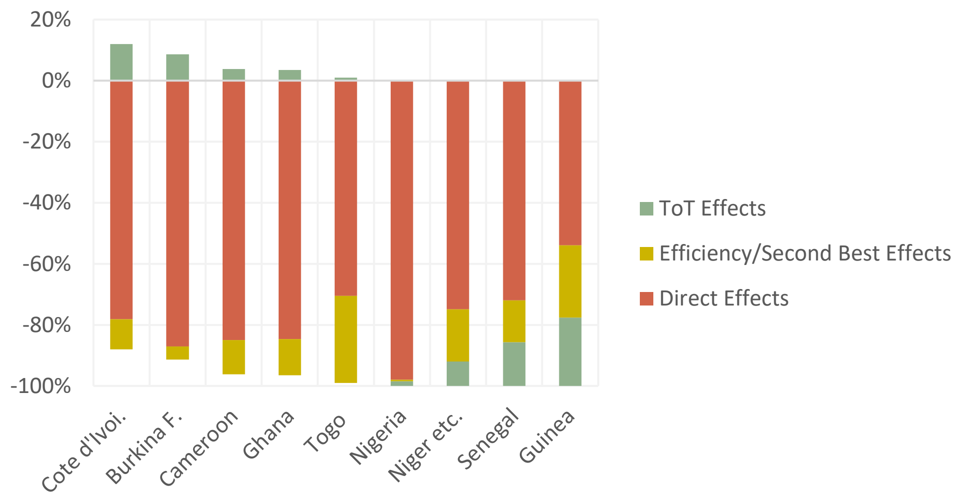


Figure 22: Decomposition of welfare changes in West African countries.

Note: "Niger etc." includes all other West African countries: Benin, Cape Verde, Gambia, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Saint Helena, and Sierra Leone.

[12] The size of ToT effects is, however, dependent on the Armington assumption and the magnitude of Armington elasticities governing trade. Appendix D reports results using larger trade elasticities representing a relaxation of the Armington-related monopoly power. In some cases, Senegal and Guinea in particular, ToT related welfare changes are then smaller.

In order to determine why some countries benefit while others are made further worse-off by trade effects, our starting point is the decomposition of terms-of-trade changes in these countries, illustrated in Figure 23. As detailed in the methods section, a country's terms-of-trade is a summary statistic that accounts for general world prices of the goods that it trades, the prices of its export goods relative to the world price of those goods, and the prices of its import goods relative to the world price of those goods. Figure 23 shows that aggregate ToT changes in these countries are being driven by either changes in world prices (of the goods they trade), or changes in their (country-specific) export prices (relative to the global average). Cote d'Ivoire has the largest improvement in its ToT driven in large part due to the increasing world prices of its net exports . Cote d'Ivoire's largest next export shares are for "other crops" (primarily coffee), "other foods" (primarily frozen fish), and "vegetables, fruits, and nuts" (primarily cashews and bananas). In contrast, Burkina Faso experiences a ToT improvement driven almost entirely by increasing prices of some of its exports of plant fibers, oilseeds, and vegetables and fruits[13]relative to world prices of these same goods. In other words, Cote d'Ivoire happens to be a net exporter of goods whose prices are driven up world-wide. While in Burkina Faso, prices of the goods it exports rise faster than they do in the rest of the world, because it is affected more acutely by heat stress. Thus, the two countries see beneficial trade effects but for differing reasons. At the opposite end, Guinea and Senegal mirror Cote d'Ivoire and Burkina Faso, respectively. In the case of Guinea, its ToT deteriorate, driven by falling relative world prices of crude oil which it export and rising prices of other crops that it imports. . While Senegal's ToT deteriorate due its country-specific export prices (of non-ferrous metals and other food) falling.

[13] Burkina Faso also exports gold and crude oil (these are its largest exports) which contribute negatively to its ToT change but the larger increases in the prices of its agricultural exports are dominant.

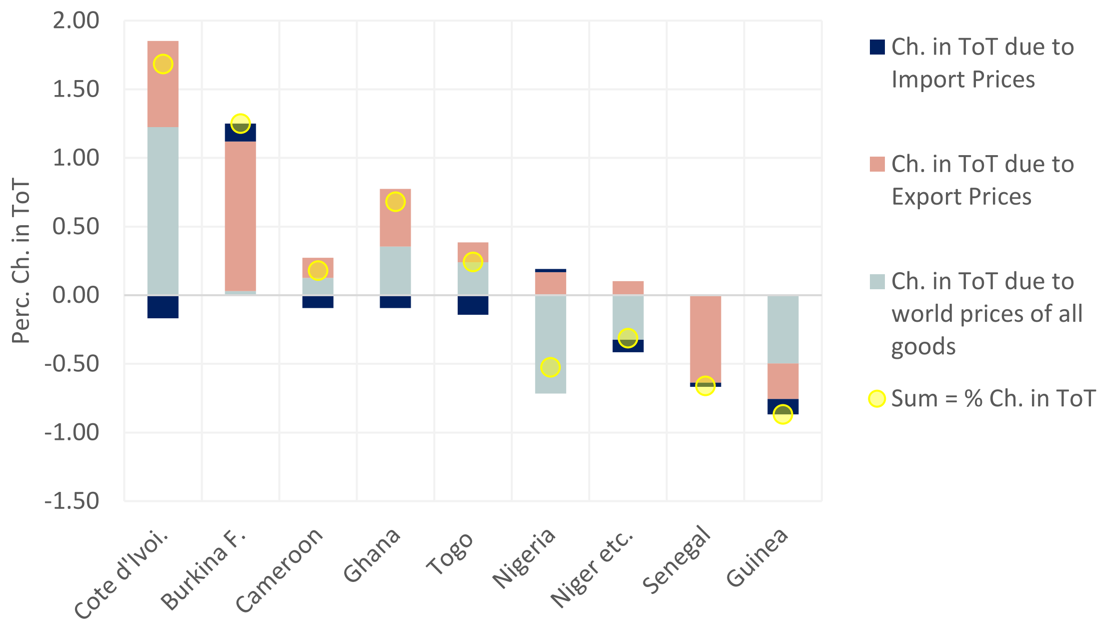


Figure 23: Decomposition of Terms of Trade (ToT) changes

Note: "Niger etc." includes all other West African countries: Benin, Cape Verde, Gambia, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Saint Helena, and Sierra Leone.

These differences across countries, that is, which component drives terms of trade changes, and the direction of these changes, is explained by differences in what commodities these countries export and import. For example, large portions of Cote d'Ivoire's net exports are "other crops" (coffee), "other food" (frozen fish), and vegetables and fruits (cashews and bananas). Figure 24 shows that these sectors see some of the largest increases in global prices. Thus, the combination of large increases in world prices and a large share in Cote d'Ivoire's net exports yields a large world price-driven ToT improvement for the country.

Burkina Faso, on the other hand, exports non-ferrous metals (gold), crude oil, and also fiber crops (cotton). While global prices of fiber crops increase (relative to other goods), for crude oil they fall (more specifically, prices for crude oil do not increase relative to all other goods). The two effectively cancel each other out so that world prices do not appear in Burkina Faso's overall ToT change in Figure 22.

At the other end of the distribution, Guinea is a large net importer of processed rice and is therefore hurt by the large global increase in the price of rice (seen in Figure 23). At the same time, Guinea's largest export is crude oil, whose global price (relative to other goods) falls. This results in global prices playing a negative role in Guinea's ToT from both the import and export side.

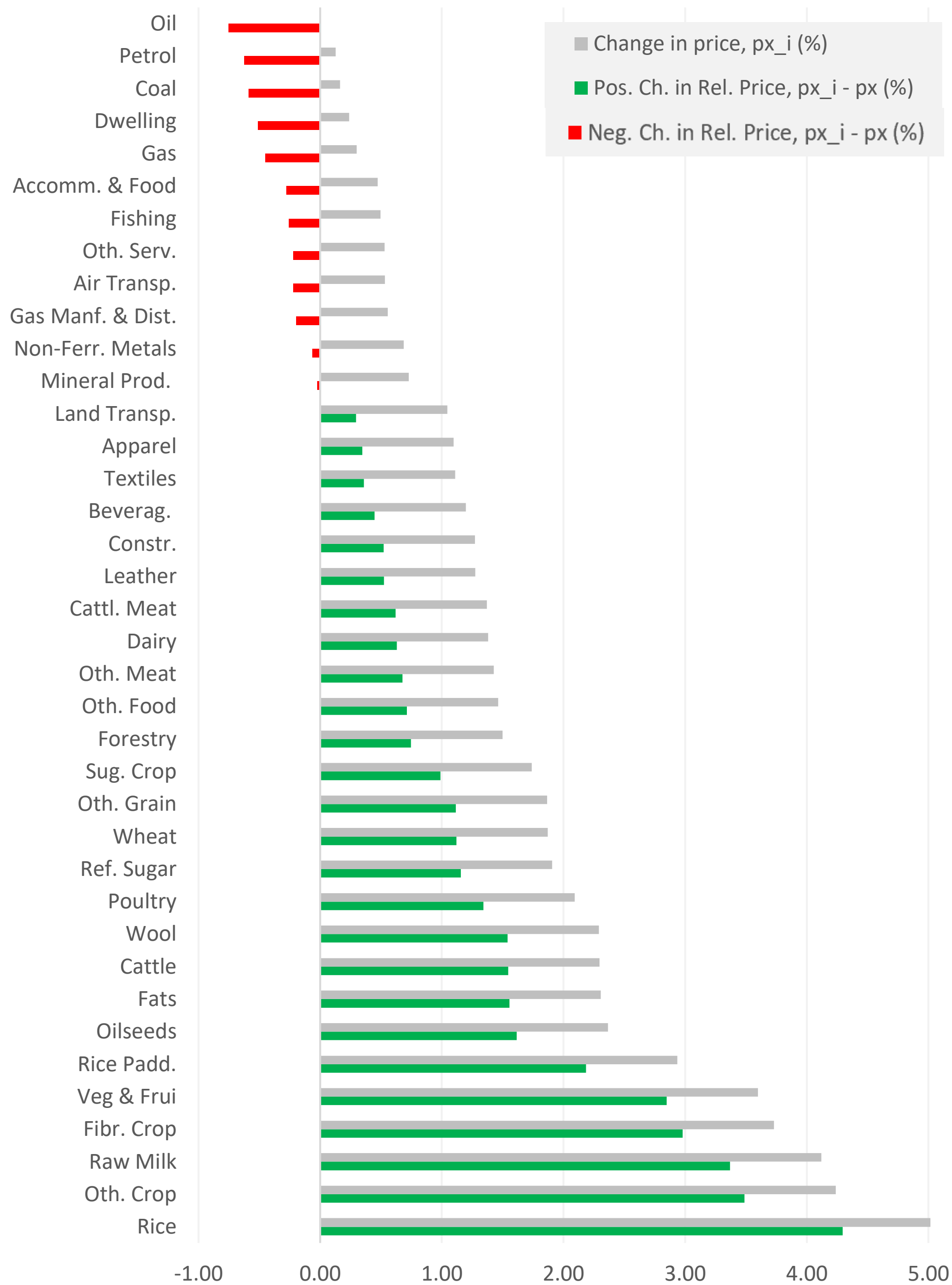


Figure 24: Percentage changes in world export prices by sector (px_i) and percentages changes in relative export adjusted for average global price increase(px))

We can generalize these patterns as follows. Countries that are net exporters of "green" sectors in Figure 24 will tend to benefit from the global price changes that result from heat stress-induced labor capacity losses. Net importers of these sectors, on the other hand, will be negatively affected by trade. On the other hand, countries that are net importers of "red" sectors in Figure 24 will benefit while those that are net exporters will be negatively impacted.[14]

Changes in global prices are but one component of a country's ToT in Figure 23. The other component that plays a significant role in the sample of countries are country-specific export prices. If a country's export prices (of any sector/commodity) rise more or less than the global average (for that sector/commodity), its ToT are improved or worsened more so. For example, in the case of Cote d'Ivoire not only do world prices of its major exports rise ("other crops", and vegetables and fruits) but its export prices of these commodities rise more than the global average, improving terms of trade further.

3.4.4 Subtotals – underlying drivers of ToT changes in West Africa

In this section, we determine the role of trade in affecting regional welfare using an alternative decomposition approach. We consider that in our experiment, heat stress affects each region in two ways. There is a direct impact as each region suffers labor productivity losses itself; and indirect impacts due to other regions being affected by labor productivity losses. Thus, a country unaffected by heat stress itself can nonetheless experience economic consequences in an integrated global economy.

As described in the methods section, we decompose our outcomes of interest in a way that is analogous to performing separate experiments but has the advantage of allowing the subtotals to sum up to the total impact on welfare. In our case, this allows us to separate the impacts of heat stress in each individual West African region from the impacts of heat stress in other countries. That is, we assess how much each West African country is affected by its own heat-stress, relative to how much it is affected by heat stress abroad.

Figure 25 summarizes the ToT results decomposed in this way. It shows that "Rest of World Effects" are frequently large and dominant. For example, Cote d'Ivoire's ToT improve more so due to heat stress affecting other countries (in West Africa as well as the rest of the world) rather than its "own" heat stress. Given that it is an exporter of agricultural commodities, and these

[14] Note that "red" sectors include coal, crude oil, and petrol products. These commodities experience falling supplies as well as increasing demand, both of which contribute to their prices increasing, relative to the numeraire which is a global index of primary factor prices. This is shown by the grey bars in Figure 24. However, other sectors (especially agriculture) experience much larger price increases. As a result, the increase in global average prices is larger, and hence sectors such as coal, oil, and petrol see falling *relative* prices as shown by the red bars in Figure 24.

become more valuable in a warmer world, Cote d'Ivoire is a beneficiary of heat stress affecting other countries which drives up agricultural prices globally. Ghana and Senegal also are beneficiaries of heat stress abroad albeit to a lesser degree. Other countries in West Africa are not fortunate in this way: they are frequently negatively impacted by heat stress in other countries. Comparing these results and the composition of exports in Section 3.4.1 across these countries shows a correlation between larger shares of agriculture and food in a region's exports and a tendency to benefit from "rest of world" effects. The West African countries with negative impacts from the rest of the world tend to have greater reliance on exports of non-ferrous metals.

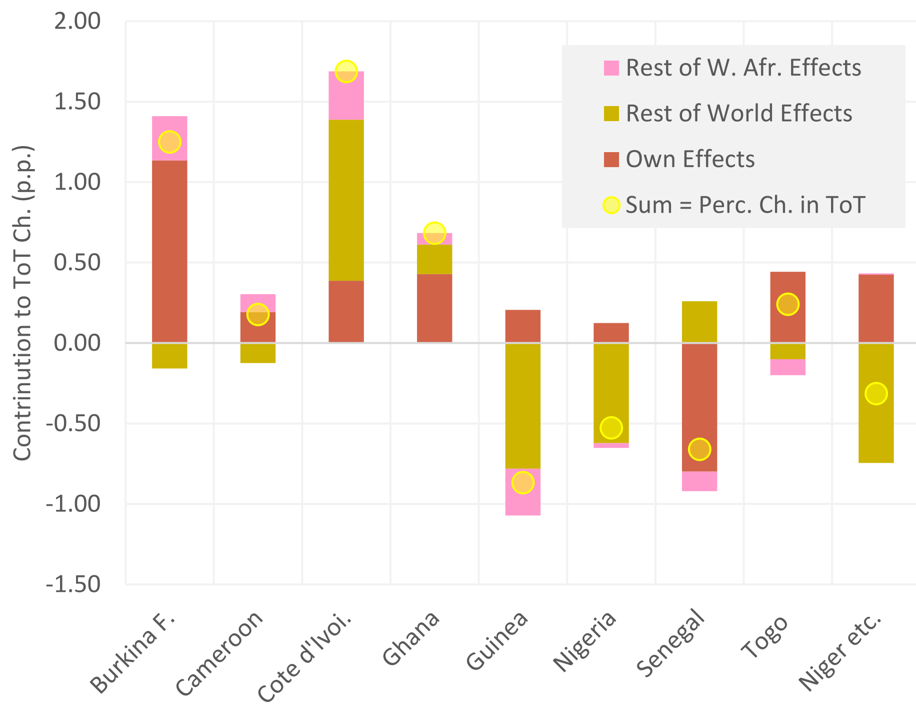


Figure 25: Changes in Terms of Trade by country, due to heat stress labor productivity loss in (i) own country, (ii) in all other West African countries, and (iii) in all other rest of world

Figure 26, Panel A shows a more detailed version of Figure 25, where "Rest of West Africa effects" are further broken down by specific country. It shows, for example, that Burkina Faso is beneficiary of heat stress in Cote d'Ivoire, while Cote d'Ivoire is a beneficiary of heat stress in Nigeria. In the remaining panels, each component of ToT is decomposed similarly to determi-ne whether changes in each component are driven by the country's own productivity losses or by the productivity loss in West Africa or in rest of the world. Given that each of the country's export mostly to countries outside of West Africa, the role of other West Africa countries generally small.

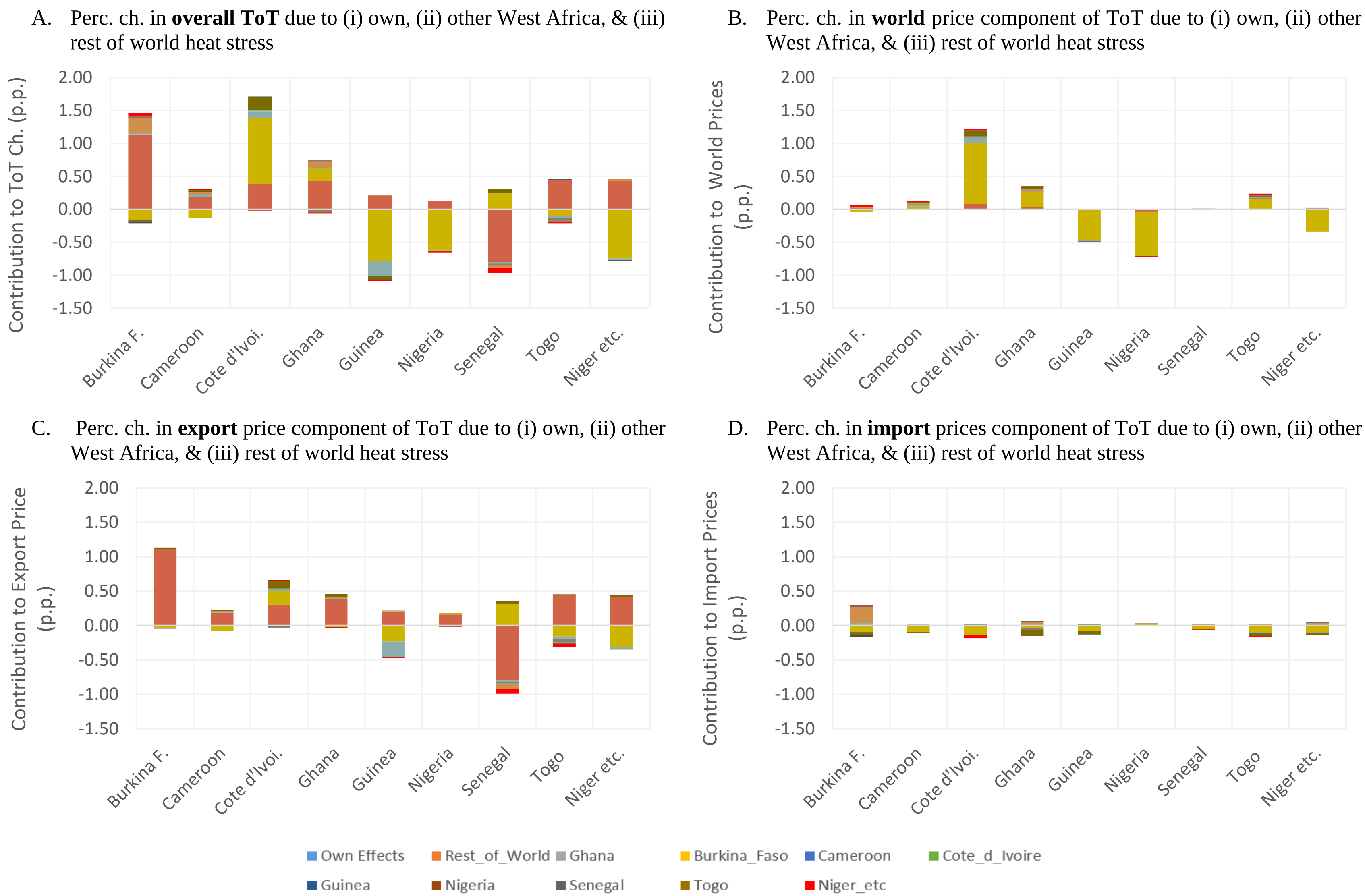


Figure 26: Changes in Terms of Trade and its components by country, due to heat stress labor productivity loss in (i) own country, (ii) in all other West African countries, and (iii) in all other rest of world

3.5 Discussion

In this chapter, we have delineated the role of international trade when countries across the world are affected by heat stress-induced labor capacity losses. We show that, with the exception of countries that lie closer to the poles, labor capacity losses consistently negatively impact the economic welfare of most economies in and around the tropics. In contrast, welfare impacts that are caused by terms of trade changes are heterogenous. That is, some countries see terms of trade improvements as a result of our simulated heat stress shock, while others see deteriorations. Within West Africa, the region we focus on as our case study, of the nine economies we consider, five see a ToT improvement and four see a deterioration.

In order to explain why heterogenous ToT changes occur across these nine West African economies, we first identify what drives terms of trade changes in terms of its component parts across these countries. We found that changes in world prices can often play a larger role in driving overall terms of trade changes than countries' own region-specific changes in export prices (relative to world prices). Countries that are net exporters of agricultural commodities are, in particular, beneficiaries of global prices changes since these rise most sharply. On the other hand, global price changes work against net exporters of mining commodities (e.g., crude oil) and closely related products (such as non-ferrous metals, non-metallic minerals). Net exporters of these see their welfare losses exacerbated by trade effects. This is because, while prices of these commodities do increase, relative to other commodities (in particular agricultural produce), they fall. Hence, countries that export these see a deterioration in their terms of trade.

However, as shown by the decomposition of ToT in our analysis, global price changes form only one component of a country's ToT. In the case of our experiment, the other component that sees significant changes, is related to region-specific export prices. Cote d'Ivoire sees the largest terms of trade improvement and serves as an illustrative example. It is a net exporter of agricultural goods whose prices are raised globally by heat stress and thus experiences a ToT improvement from the global price component. But, further to this, because of the higher heat stress in the region, agricultural prices in Cote d'Ivoire rise even more so than the global average. Thus, its terms of trade are improved from two different sources: global price increases that work in its favor as well as increases in prices of its specific exports. In contrast, Guinea is an importer of rice and an exporter of crude oil. Its welfare is therefore worsened by ToT effects due to global agricultural price increases (its imports become more costly) and deteriorates further because the relative world prices of crude oil falls (its exports earn less, in relative terms).

Further to this, we also identify, using an alternative approach, the extent to which each country's terms of trade changes (and changes in the component parts of its terms of trade) are driven directly by its own heat stress (-related productivity losses), and the extent to which these changes are driven by the fact that the rest of the world is also affected by heat stress (-related productivity losses). In four of the nine West African regions considered, heat stress in the rest of the world accounts for a larger portion of these country's term of trade changes than their own heat stress impacts. For example, most of Cote d'Ivoire's terms of trade improvement is the result of heat stress in the rest of the world. These findings largely reinforce the findings from the ToT decomposition which showed that global price changes often drive individual country's terms of trade changes.

More generally, we find that while heat stress-induced labor productivity losses cause global increases in prices in general, of most sectors/goods, prices of agricultural and related food commodities increase most sharply. And, while mining and closely related manufacturing sectors also see some price increase, in relative terms (relative to an index of all global commodity prices) their prices fall. Countries that can benefit from (or more precisely, see their welfare losses mitigated by) trade effects in a warmer climate will be (i) net exporters of agricultural (and closely related) commodities regardless of their domestic heat stress, and (ii) countries whose exporting sectors see price increases more acutely than the global average. Cote d'Ivoire is an example of a country that fall under both categories. In contrast, Burkina Faso falls only in the second category. These heterogeneous trade/ToT effects in our results across countries in West Africa, provides some support for efforts towards greater trade integration in the region. Our results suggest that aggregate welfare, in the face of heat stress, could be improved if the region became more integrated, allowing for the region to disperse the negative effects through trade. This, however, requires more comprehensive policy-focused analysis that we leave for future work.

It is also worth emphasizing here that these countries are in general harmed by heat stress – and those that fall in the second category (ii above) are those that experience especially high heat stress. Our results only indicate that when this is the case, trade offers some mitigation of these countries otherwise large economic welfare losses. We also find that the global nature of heat stress often has a greater impact on individual economies' terms of trade than does their own domestic heat stress. In other words, even if these countries experienced no heat stress themselves, they would still experience terms of trade changes in the directions observed.

3.6 References

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CHAPTER 4. THE POVERTY IMPACTS OF LABOR HEAT STRESS IN WEST AFRICA UNDER A WARMING CLIMATE

4.1 Introduction

In this chapter, we continue in the area of the global macroeconomic impacts of heat-stress-induced labor-productivity losses. Our focus in this case is on poverty and as in Chapter 3 we use the case of West Africa to better understand and delineate the channels by which poverty will be impacted. As has been described previously, with climate change and the subsequent increases in heat, workers' capacities will be diminished across the world. In turn, cascading global economic effects, driven by sectoral and regional interdependencies, result. Recent studies that have assessed the resulting output and GDP losses across the globe using general equilibrium methods show that the largest GDP declines ranging from 1% to 4.2% would occur in Africa and South Asia (Orlov et. al., 2020; Knittel et. al., 2020; de Lima et. al., 2021). These regions comprise low-income economies that are home to a large share of the world's present-day poor, which raises questions as to the extent to which international poverty reduction goals could face significant headwinds due to this aspect of climate change.

In this chapter, we therefore assess the poverty implications of heat-stress-induced labor capacity losses and elaborate the factors and mechanisms that determine the direction and magnitude of changes in the poverty headcount in a particular country. To do this, we consider seven West African countries for which the necessary household data were available. These are Ghana, Burkina Faso, Cameroon, Cote d'Ivoire, Guinea, Nigeria, and Senegal. To assess poverty impacts, we use a macro-to-micro approach. That is, a global general equilibrium "macro" model is used to assess global economic impacts (as in Chapter 3). This includes impacts on prices of commodities and returns to factors of production. These price changes, along with our estimates of labor productivity losses, are then used as inputs into a household microsimulation exercise for each of the seven countries of focus using household income survey data. In this way, we assess how significantly the poverty headcount could be affected across these different countries that vary in economic structure and in the number and composition of poor households (see Section C of the Appendix).

Our methodology also differentiates between different household types within each country (for which poverty is assessed). More specifically, we account for the fact that low-income households (those that lie close to the poverty line) are heterogenous in how they earn their incomes as well as their consumption patterns. For example, rural agricultural households will differ considerable from urban poor households in terms of the commodity prices and factor returns that are important in determining their real incomes and hence poverty outcomes. In other words, poverty impacts, their direction and relative magnitude, varies not only across different countries but also across different household types within each country. Thus, to gain a complete understanding of the determinants of country-level poverty results, we further narrow our focus to one country, Nigeria, for which we fully decompose the drivers of the country-level poverty results. Out of the seven countries that we sampled, Nigeria is the largest in terms of population and, as our results will show, experiences the largest poverty impacts in our experiments.

This chapter therefore builds on and complements the growing number of studies[15] that focus on the assessment of the broad economic impacts of heat stress in labor. These previous studies provide important insights into the potential GDP and output losses that would result from heat stress in labor across broad regions of the world. However, our study makes the following additional contributions. Foremost, it provides an assessment of the impacts on the poverty headcount which to our knowledge has yet to be addressed specifically in the literature. Furthermore, our analysis is highly disaggregated relative to past work. We disaggregate the global economy into 137 regions, 65 sectors, and we also consider 4 different labor types (as opposed to one composite labor). Past studies use broad region and sector aggregates. Further still, for our analysis at this highly disaggregated level, we construct new estimates of labor capacity losses that are region-, sector-, and labor type-specific, using more precise methods than previous studies and using additional data. Thus, our study also serves as a re-examination of labor capacity losses estimated in past studies.

The remainder of this chapter is organized as follows. Section 4.2 reviews these previous studies in detail. Section 4.3 describes our methods including the assessment of heat stress and labor capacity losses; and our approach to assessing poverty. Section 4.4 presents our results and Section 4.5 provides a discussion of our findings.

[15] These include Orlov et. al. (2020), Knittel et. al., (2022), and de Lima et. al. (2021).

4.2 Related literature

Two bodies of literature are closely related to the analysis undertaken. The first is the body of literature that focuses on assessing heat stress and labor capacity losses. Key studies in this area include Dunne et. al. 2013, and Bröde et. al. 2018. These studies are not discussed at length here. We only mention that they provide methods for assessing how much labor capacity is impacted when affected by heat stress. Our approach relies on the labor capacity function of Bröde et. al., 2018. This function allows us to estimate human labor capacity at any given level of heat stress as measured by the Wet Bulb Globe Temperature (WBGT), and assuming that workers follow work-rest cycles consistent with an international work place safety standard. The WBGT, the Bröde labor capacity response function, and its calibration are described further under the methods section.

The second body of studies that are closely relevant are those that, like our analysis, address the global economic implications of labor productivity losses. We focus here on studies that use global general equilibrium methods and therefore account for market responses, sectoral dependencies, and global trade dependencies. These include Lima et. al. 2021, Orlov et. al. 2020, as well as Knittel 2021 (which was previously discussed under Chapter 3). Each of these studies takes the same broad approach of employing a global general equilibrium economic model to simulate labor capacity losses determined using methods developed in the scientific literature described above. These assessments are however inevitably uncertain, not only due to climate uncertainty but also due to the methodological choices that must be made.

More specifically, the assessment of the global economic impacts of heat-stress induced labor capacity losses entails the following steps. First, climate models are used to determine projections of future heat stress. This requires choices to be made over alternative climate model(s), climate scenarios, heat stress metrics, as well as choices regarding the geographic and temporal resolution of these projections. Next, these heat stress projections are translated into projections of labor capacity losses. Here choices must be made with regards to which methods/labor capacity response function to use, and how these are calibrated. Additionally, assumptions may also be needed with regards to the intensity of physical activity and the frequency or duration of outdoor exposure. For example, we may estimate how productivity is affected of a worker who is constantly performing high intensity labor outdoors (e.g. an agricultural or construction worker doing manual labor), or how productivity is affected for a worker performing physical labor at a lower intensity indoors (e.g. a worker in a factory assisted by machinery). Finally, the economic implications of these projected labor capacity losses are determined. Here, a choice must be made regarding the economic framework to be used, and furthermore, regarding how labor capacity losses are implemented or interpreted within it. For example, do we simply assume all labor is homogenous within each sector? If not, how do we account for different types of workers working at different intensities and with differing outdoor exposure?

For a comparison, Orlov et. al. (2021) address these methodological choices as follows. They obtain projections of heat stress related variables (temperature, humidity, wind speed, solar radiation) using two climate models (from ISMIP), for 0.5° grid cells at daily frequency, and consider two climate scenarios (RCP 2.6 and RCP 8.5). These variables are used to estimate average daily WBGT (using approximation methods) for indoor and outdoor conditions. The WBGT projections are then used to determine projections of labor capacity losses using the Bröde exposure response function, calibrated using empirical studies, to determine labor capacity losses for indoor work and outdoor work, each of which are estimated for low-, moderate-, and high-intensity work (metabolic rates of 200W, 300W and 400W respectively). These labor capacity losses are then interpreted as sector-specific labor capacity losses as follows: agricultural and construction work is assumed to be homogenously outdoor, high-intensity (400W) labor; manufacturing work is assumed to be moderate-intensity (300W), indoor work; and labor in the services sectors is assumed to be low-intensity (200W), indoor work. Finally, with regards to choice of economic framework, Orlov et. al. use a recursive-dynamic general equilibrium model that disaggregates the global economy into 10 regions and 12 sectors. Using these approaches, Orlov et. al. provide assessments of impacts on GDP, production, and trade balances across these aggregate regions and sectors, under alternative climate scenarios. The largest GDP losses by the year 2100 occur for South Asia (6% GDP loss under RCP 8.5) and Africa (3.5% GDP loss under RCP 8.5). Sectors with the largest production losses are manufacturing and construction.

de Lima et. al. (2021), on the other hand, focus on the agricultural sectors alone. Their focus is on comparing the economic losses caused by crop yield losses and those caused by heat stress in agricultural workers. For their analysis, they use two different heat stress metrics, the sWBGT (a simplified version of WBGT that is easier to compute) and also the Environment Stress Index (ESI). using an ensemble of climate models and three different mean warming scenarios such that mean global temperatures rise by 1°C, 3°C, or 5°C. In contrast to Orlov et. al. (2020), labor capacity response functions are calibrated using safety standards (two different standards are considered). A static, general equilibrium framework is used to compare the economic losses caused by heat-stress' effects on labor vs losses caused by heat-stress' effects on crop yields, and the economic losses that occur due to the interaction of both labor productivity and yield changes. They find that in regions close to the tropics, the economic losses caused by human heat stress are comparable to those caused by crop yield losses.

As noted earlier, this study extends this literature by providing an assessment of poverty impacts in West Africa, and in doing so re-examines labor capacity losses using more precise methods, assesses these at a far more disaggregated level (for 137 countries/regions, 65 sectors and 4 labor types).

4.3 Methods and data

4.3.1 Overview of methods

To assess the poverty implications of heat stress induced labor capacity losses, this paper broadly follows a path similar to that of the recent economic assessments described above. This entails the following major steps. (i) We first quantify heat stress intensification by comparing a baseline period (1961-1990) with a 3^{o}C global mean warming scenario. Heat stress is measured by the WBGT which we calculate using Liljegren et. al. (2008)'s formulation which avoids the ad-hoc approximations used in prior studies (Orlov et. al., 2020; Knittel et. al., 2020; de Lima et. al., 2021). (ii) The resulting labor capacity losses are then determined using the labor response function of Brode et. al., (2018) wherein we apply the ISO Standard 7243 (ISO, 2017). That is, we assume work-place safety standards designed to prevent mortality and morbidities are followed. (iii) These labor capacity losses are then used as inputs into a global general equilibrium economic model. In this paper, we use the GTAP-POV model (Hertel et. al., 2011). (iv) The central innovation in this paper is the assessment of impacts on impoverished households, as well as the overall poverty headcount. We assess these using price and wage changes determined by the main global general equilibrium model as inputs into a micro module (described in later sections) which permits us to make inferences about changes in the poverty headcount nationally as well as by type of household.

These steps – the broad methods and key data sources used – are summarized in Figure 27 while detailed descriptions are provided in the sections that follow.

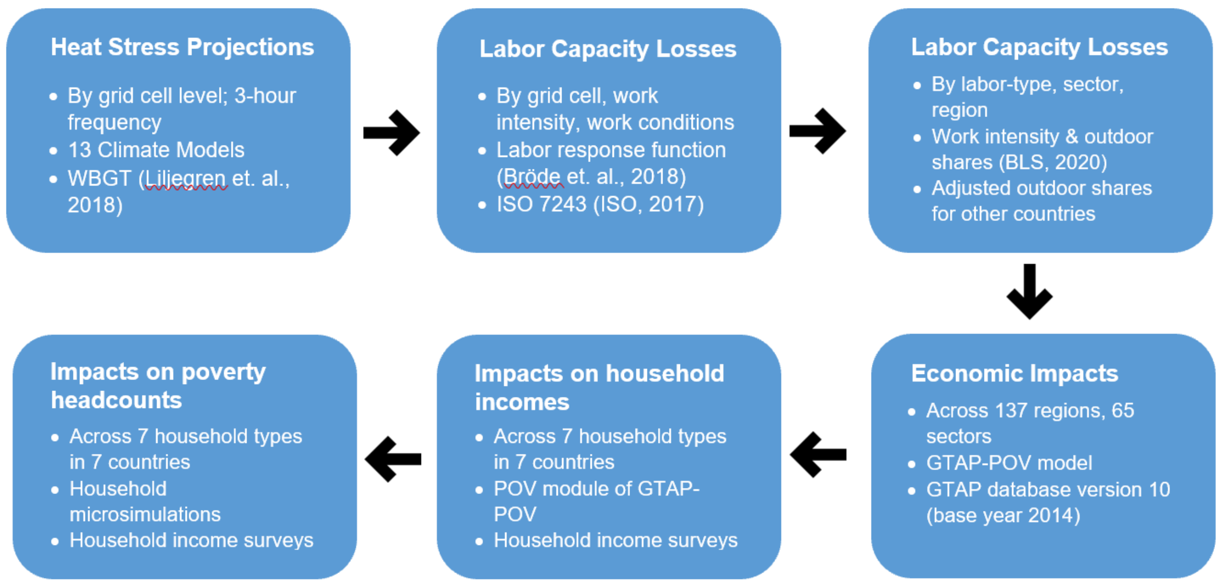


Figure 27: Overview of methods and data used for the assessment of the poverty implications of heat stress-induced labor productivity losses

4.3.2 Estimation of WBGT

As mentioned, in this study, heat stress is measured by WBGT. WBGT is a widely used heat stress metric that incorporates the effects of all four ambient factors (temperature, humidity, wind and radiation). It has well-established safety thresholds within the athletic (American College of Sports Medicine, 1984), occupational (Coco et. al., 2016) and military settings (Sawka et. al., 2003). However, WBGT is not available as a routine meteorological measurement, and various approaches have been developed to approximate it. The simplified WBGT (ABM, 2010) and environment stress index (ESI) (Moran et. al., 2001; Moran et. al., 2003) represent two relatively simple *ad hoc* approximations. However, these are subject to potentially large biases when used out of the conditions under which they were developed (Grundstein & Cooper, 2018; Havenith & Fiala, 2011; Kong & Huber, 2022). Instead, we use a physically-based model developed by Liljegren et al. (2008) to directly simulate WBGT measurements.

Liljegren's model has been extensively calibrated and validated (with an RMS difference of less than 1°C) and has seen increasing applications in recent years (Takakura et. al., 2017; Casanueva et. al., 2020). Kong and Huber (2022) developed a Python implementation of Liljegren's code (originally in FORTRAN and C language) which is especially suitable for processing large-size climate model output and is adopted for our analysis. For the detailed calculation procedure of WBGT, see Liljegren et. al. (2008) and Kong and Huber (2022).

4.3.3 Projection of future heat stress

To determine future WBGT levels (using the Liljegren approach), we retrieve inputs from 10 climate models (13 ensemble members) within the CMIP6 archive at 3-hourly frequency. These are listed in Section A of the Appendix. The retrieved inputs include 2m air temperature, surface specific humidity, surface pressure, 10m wind, and surface downward and upwelling components of both short- and long-wave radiation. WBGT is calculated under both outdoor and indoor conditions. For indoor conditions, solar radiation is set to zero and wind speed is fixed at 1m/s.

Heat stress intensification is quantified by comparing heat stress under the baseline period of 1961-1990 with that under 3°C warming of global mean surface air temperature. The SSP585 scenario is used to evaluate heat stress under 3°C warming. More specifically, each year in the SSP585 simulations is indexed by the degree of warming compared with the baseline period, and years with 2.75 to 3.25°C warming are used to represent a 3°C warmer world.

By focusing on labor loss at a certain warming target, we decouple our analysis from the time-path of forcing, thereby reducing uncertainties caused by model spread due to climate sensitivity. This approach has the advantage that our results are not sensitive to the driving scenario since the GCM results are scaled to specific warming levels and these responses are robust (Buzan & Huber, 2020). This removes issues related to "when does warming happen" and "what scenario of emissions is being followed". In addition, bias correction is conducted by adding WBGT anomalies from CMIP6 climate models onto a common ERA5 reanalysis baseline (1961-1990) (Hersbach et. al., 2018).

4.3.4 Estimation of labor capacity losses

Next, the projections of heat stress/WBGT are translated into projections of labor capacity losses. This is done using work-rest cycles proposed by international safety standards (ISO, 2017) in order to prevent human body core temperature exceeding 38°C[16]. We begin by identifying a

[16] By taking this approach, we are effectively estimating the economic and poverty-related costs of preventing increased mortality and morbidity due to heat stress in labor. In practice, we can expect that international safety

reference value of WBGT ($WBGT_{lim}$) corresponding to the upper limit of the prescriptive zone. Workers are recommended to work for only a fraction of each hour when the environment WBGT values exceed this reference value. $WBGT_{lim}$ can be calculated by the equation below which is adopted by both ISO 7243 (ISO,2017) and NIOSH (Coco et. al., 2016):

$$WBGT_{lim} = 56.7 - 11.5 \log_{10} M \tag{30}$$

where M refers to metabolic heat production rates in Watts. Labor capacity can be then obtained by:

$$labor\ capacity = \max\left\{0, \min\left[1; \frac{WBGT_{lim,rest} - WBGT}{WBGT_{lim,rest} - WBGT_{lim}}\right]\right\} \tag{31}$$

where $WBGT_{lim,rest}$ refers to the limit WBGT value when people are at rest ($M = 117W$).

In implementing the labor response functions as described above, assumptions must be made with regards to the intensity of physical activity (the value of M in Equation 1) and the conditions under which this activity takes place, outdoors or indoors (shaded). In this study, we take the approach that for every grid-cell, we obtain labor capacity declines for four different levels of work intensity ranging from light work to very heavy work (metabolic outputs of 200W, 300W, 400W and 600W). Each of these is estimated under both indoor and outdoor conditions. The percentage decline in labor capacity under 3°C warming is estimated relative to baseline period labor capacity.

In past studies, simplistic assumptions were used to assign these labor capacity losses to economic sectors, such as assuming all agricultural labor is done at a single work intensity (e.g. M is assumed to be 400W) and entirely indoors or outdoors. For our analysis, rather than apply one intensity-exposure profile to a particular sector, we use data from the United States Bureau of Labor Statistics (BLS, 2020) to assign weights to these different estimates and produce labor capacity losses that apply to specific labor types within specific sectors and countries. The BLS data identifies the types of workers employed in different sectors and provides descriptors regarding their intensity of work (ranging from “sedentary” to “very heavy”), and their exposure

standards are often not followed and thus in this regard our estimates of labor productivity losses can be considered to be an upper limit, and actual labor productivity losses may be smaller. The alternative would be to use empirically determined labor productivity losses. However, this approach would have the disadvantage that the increased costs associated with increased mortality and morbidities would need to somehow be accounted for.

to the outdoors (ranging from "never" to "constant"). We map these descriptors to specific assumptions about metabolic output (e.g., we assume "very heavy work" is equivalent to metabolic output of 600W). These assumptions are reported in Table 8.

Table 8: Assumed mapping of work intensity descriptors to working rate in watts

BLS Intensity Descriptor	Assumed Metabolic Output
Sedentary	0
Light work	200W
Medium work	300W
Heavy work	400W
Very heavy work	600W

Formally, we estimate:

$$z_{l,a,r,g} = \sum_{c} \sum_{i} z_{r,g}^{i,c} \ \alpha_{l,a}^{c} \ \beta_{l,a}^{i} \tag{32}$$

where $z_{l,a,r,g}$ is the labor capacity loss of labor type l in activity a in grid-cell g of region r. These sector-specific labor-capacity losses are obtained by applying weights to $z_{r,g}^{i,c}$: the percentage decline in labor capacity in grid-cell g (in region r), for work performed at intensity i where $i = \{200W, 300W, 400W, 600W\}$, and in indoor or outdoor conditions indicated by the index c where $c = \{indoors, outdoors\}$, under heat stress levels consistent with 3°C mean global warming. The weights in question are: $\alpha_{l,a}^{c}$ the portion of time that labor type l in activity a is exposed to work conditions c, and $\beta_{l,a}^{i}$, the portion of work of labor type l in activity a that is performed at work intensity i.

The BLS data are, however, specific to the U.S. economy and the shares $\alpha_{l,a}^{c}$ which measure exposure to outdoor work of different labor types in different sectors could be a poor approximation of work conditions in low-income countries. This is especially true for agricultural workers whose exposure to the outdoors is likely to be far more frequent in low-income countries than in the U.S. We therefore adjust the shares of outdoor work by assuming that this declines (logarithmically) with a country's GDP per capita. This captures approximately the higher rates of mechanization and other technological improvements in higher income economies that may allow labor to be less exposed to outdoor conditions. (This adjustment is described in further in Section B of the Appendix).

Finally, we aggregate the grid-level labor capacity losses ($z_{l,a,g,r}$) over grid-cells to obtain region, sector, and labor specific capacity losses ($z_{l,a,r}$). To do so, grid-cells are weighted by their population when aggregating labor capacity losses for non-agricultural activities, and by their share in national agricultural production when aggregating labor capacity losses for agricultural activities. This step is described in formal terms in Section C of the Appendix.

4.3.5 Economic framework

As described in the previous section, we determine labor capacity losses that are specific to countries, labor types, and sectors. These losses are treated as labor productivity shocks in a global general equilibrium economic model, GTAP(Corong et. al., 2017; Hertel, 1997)[17]. More specifically, we employ elements of GTAP-AGR (Keeney and Hertel, 2005) and GTAP-POV (Hertel et. al., 2011). As in GTAP-AGR, we introduce segmentation in the market of labor such that labor is not perfectly mobile across agricultural and non-agricultural sectors. That is, we assume that agricultural labor cannot seamlessly transfer from agricultural to manufacturing and services, and vice versa.

For the estimation of poverty impacts we use elements of GTAP-POV, an extended version of the standard GTAP model. The standard POV extension estimates changes in the real incomes of households near the poverty line, and the resulting poverty changes using an elasticity approach. However, we deviate from the standard GTAP-POV elasticity approach and, for greater precision, instead use a household microsimulation that is described in the next section.

The underlying economic database for the main model is version 10 of the GTAP database (Aguiar et. al., 2019) which has a base year of 2014. That is, global GDP and trade patterns are consistent with a 2014 global economy. The analysis undertaken is static. In other words, the approach we have taken is to impose labor capacity losses associated with a future climate (one of 3°C mean global warming) on to a present day (2014) economy. This allows us to identify the mechanisms that drive our results with relative clarity and avoids projecting what the global

[17] The macro model and the implementation of labor productivity shocks are identical to those used in Chapter 3.

economy might look like in a distant future (when an outcome such as 3°C mean global warming might come to pass). In order to assess poverty, such a projection would require us to somehow estimate who will be poor in the future, where they live, how they earn their income, and so on. This would introduce enormous uncertainties and make results difficult to interpret since they would be driven by a combination of economic mechanisms and the assumptions made to achieve a projection of the future economy. By taking a comparative static approach, this complication is avoided and the economic mechanisms at play are easier to identify.

4.3.6 Estimation of poverty impacts

Changes in poverty are estimated using a household microsimulation approach as follows. The main GTAP model determines economic impacts which includes changes in the prices of consumption goods and factors of production. In turn, these price changes are used as inputs to estimate changes in real incomes of households close to the poverty line in the POV extension. Finally, changes in real income are used to estimate changes in poverty using a microsimulation approach. This last step departs from the standard GTAP-POV approach which estimates poverty impacts using an elasticity approach, which can be seen as an approximation of the microsimulation approach adopted here. Key elements of these steps are summarized as follows, while a detailed exposition of GTAP-POV is provided in Hertel et. al., (2011).

For each country included in the poverty module, using household survey data, we first identify households that are "in the neighborhood of the poverty line". This is defined as the decile of households that encompass the $1.90-per-day international poverty line as defined by the World Bank (Ferreira et. al., 2016). These households are then classified into seven strata based on how they earn their income. For example, households are classified as "agricultural" if they earn 95% or more of their income from agricultural self-employment, and as "urban labor" if they earn 95% or more of their income from wages. If households are not specialized, in that they do not earn 95% or more of their income from either self-employment or wages, then they are classified as rural or urban diverse. In this way, the module takes into account that poor households are heterogenous in how they earn their income. Next, the specific profile of the households within each stratum in terms of earnings shares is determined. For example, for households in the agricultural stratum in each country we determine the share they earn from land, capital, unskilled agricultural labor, unskilled wage labor, etc. The real income of households within each stratum depends on these earnings shares, and for our analysis we also account for the loss of earnings from labor due to the direct effect of heat-stress-induced productivity loss which is tied to the type of labor supplied. Formally, we determine the percentage change in the real income of households in a stratum s (in region r) as:

$$\hat{y}_{r,s} = \sum_{j} \alpha_{r,s,j} \left(\widehat{W}_{r,j} - \hat{Z}_{r,j} - \hat{C}_r \right) \tag{33}$$

where $\alpha_{r,s,j}$ are the aforementioned earnings shares; i.e., $\alpha_{r,s,j}$ is the share of income of households in stratum s in region r earned from factor j. $\widehat{W}_{r,j}$ is the percentage change in the price of (returns to) factor j determined from the main macro model, and $\hat{Z}_{r,j}$ is the loss of productivity of factor j. Earnings are also adjusted by C_r, the real cost of living of households at the poverty line given changes in consumption prices and consumption patterns of poor households in region r.

Given these changes in the real incomes of households, we determine changes in the poverty headcount using a microsimulation approach. As mentioned, this approach is used in place of the elasticity approach that is implemented in the GTAP-POV model. The household microsimulation approach is more direct and exhaustive: we consider each individual household in the neighborhood of poverty; shock its income by the size of $\hat{y}_{r,s}$; and count the number of households whose incomes fall below the poverty line. This has the advantage that it utilizes individual observations in the household survey, thereby utilizing the actual distribution of household observations as opposed to summarizing the distribution in a single elasticity metric.

The microsimulation approach is illustrated for the case of Nigeria's rural diverse stratum in Figure 28 below. It shows the distribution of rural diverse households around the poverty line, and how this distribution shifts when the incomes of households in the "neighborhood of poverty" fall by the relevant $\hat{y}_{r,s}$. As will be detailed in the results section, our results suggest a 16% increase in poverty among non-agricultural households in Nigeria.

However, this exercise must be done individually for each country for which poverty impacts are to be assessed. It is for this reason that our analysis is limited to seven countries for which the household survey data are available.

For the seven West Africa countries of focus, the household survey datasets used are as follows: Ghana Living Standard Survey 2017 (GLSS7), Burkina Faso 2014, Fourth Cameroon

Household Survey 2014 (ECAM4), Cote d'Ivoire Household Standard of Living Survey 2014 (VN2014), Guinea Limited Poverty Assessment Survey 2012 (ELEP 2012), Nigeria General Household Survey 2018, and Senegal Poverty Monitoring Survey 2011 (ESPS-II). Poverty headcount rates in the baseline are consistent with the poverty ratio at $1.90 a day (2011 PPP) (% of population) reported by the World Bank World Development Indicators database (https://databank.worldbank.org/source/world-development-indicators) retrieved in December 2021.

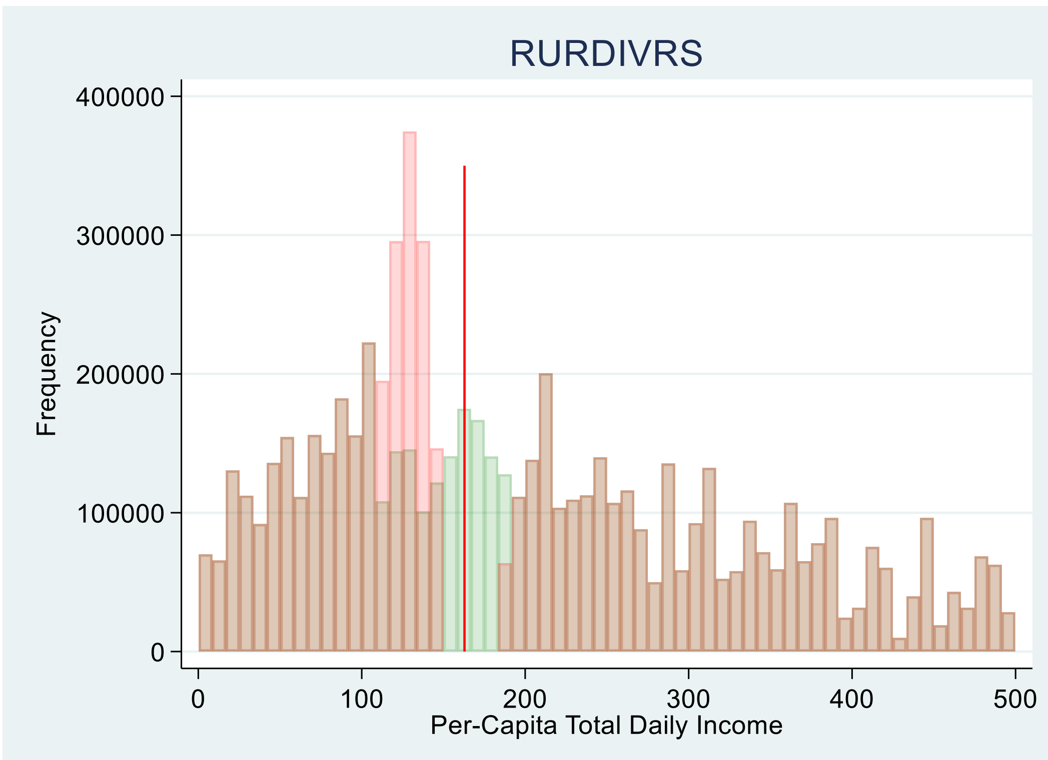


Figure 28: Household microsimulation for Nigeria's rural diverse households

Notes: Figure uses data from Nigeria's General Household Survey, 2018. Only households with per capita incomes less than ₦500 are shown. **Red vertical line** indicates the poverty line in terms of Nigerian Naira consistent with a 39.1% poverty rate as reported by the World Bank's World Development Indicators for the year 2018 based on the $1.90 per day international poverty line. **Green bars** show the original pre-simulation, baseline survey-based income distribution of households. **Red bars** show the ex-poste distribution after implementing the heat stress induced income shock estimated using Equation 4.

4.4 Results

4.4.1 Labor capacity and GDP losses across the globe

We begin by presenting our new estimates of labor capacity losses and the resulting impacts on GDP across the world. As detailed in the methods section, this paper uses a more precise formulation of the WBGT than prior studies that provide similar estimates and uses additional data to estimate labor capacity losses that are specific to labor types, sectors, and regions. Our results show that labor capacity losses are largest in South Asia and parts of the Middle East, followed by Southeast Asia and West Africa (Figure 29). In terms of these broad regional aggregates, our results are consistent with past studies. Our more disaggregated analysis, however, permits for country-specific assessments that have not been previously provided at a global scale. We find that the worst affected countries are, in order: Bahrain, Cambodia, Pakistan, Qatar, and the UAE which lose 11 to 15% of their annual labor capacity relative to the baseline[18].

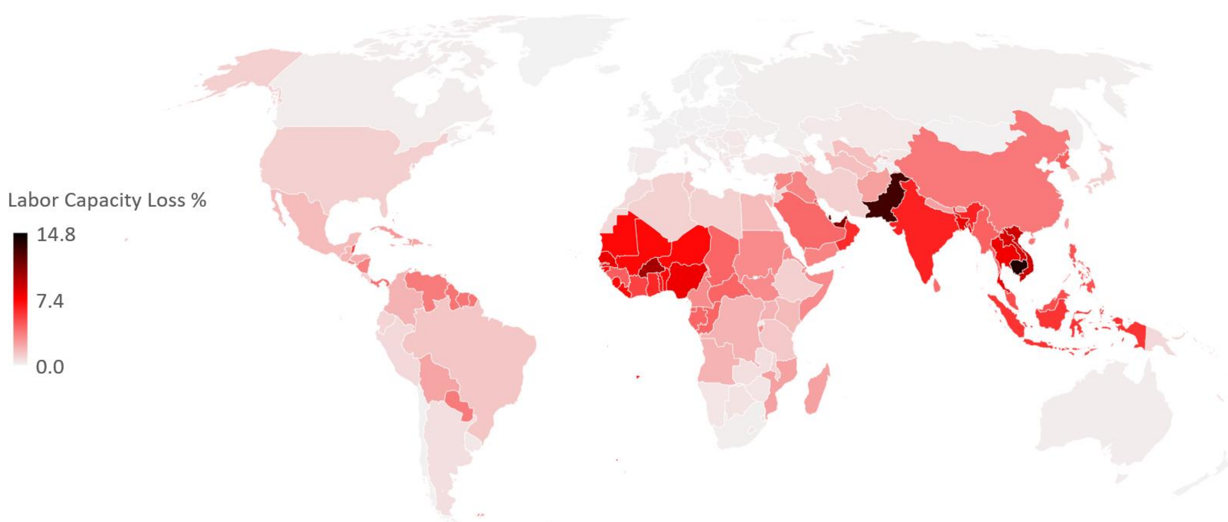


Figure 29: Country level labor capacity losses

[18] It is worth noting here that countries in the Middle East (Bahrain, Qatar, UAE) employ large numbers of migrant workers, including "blue-collar" workers in construction and extraction industries, most frequently from South Asia and Southeast Asia where heat stress productivity losses are also large. In practice, we can therefore expect impacts on international migration patterns and further impacts on wages as a result of competition for labor internationally.

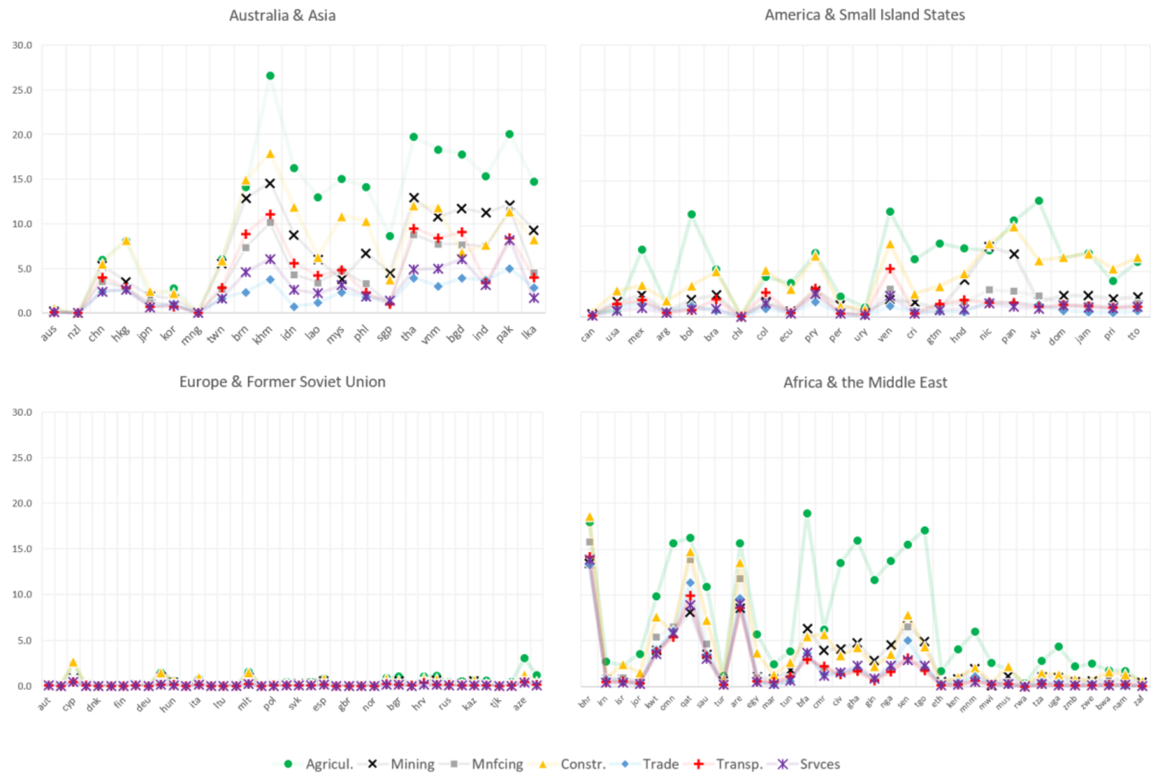


Figure 30: Labor capacity declines by region and aggregate sectors

Note: Figures shows labor capacity declines by region and aggregated sector by averaging over labor types and sub-sectors using employment in the base as weights.

However, these country-level results can mask disparities across sectors within a country. A sectorally disaggregated view is provided in Figure 30. It shows, for example, that the two single largest labor capacity losses across the globe occurs in the agriculture sector in Cambodia which loses more than 25% of its labor capacity. Agriculture in Pakistan, and in Thailand follow with labor capacity losses of 20% each. After agriculture, construction and mining sectors tend to most affected.

Global sectoral labor capacity losses, across 65 sub-sectors, are provided in Figure 31. These show that while agricultural sub-sectors experience the largest labor capacity losses, there is considerable variation across commodities, ranging from 5% for wheat to 10.3% for rice farming. At the global level, cotton (fiber crops) and rice farming (rice paddy) are the worst affected crop sectors as these crops are grown in regions of high heat and humidity – a potentially lethal combination for outdoor work. Outside of agriculture, the largest labor capacity losses are for rice processing, coal mining, and construction.

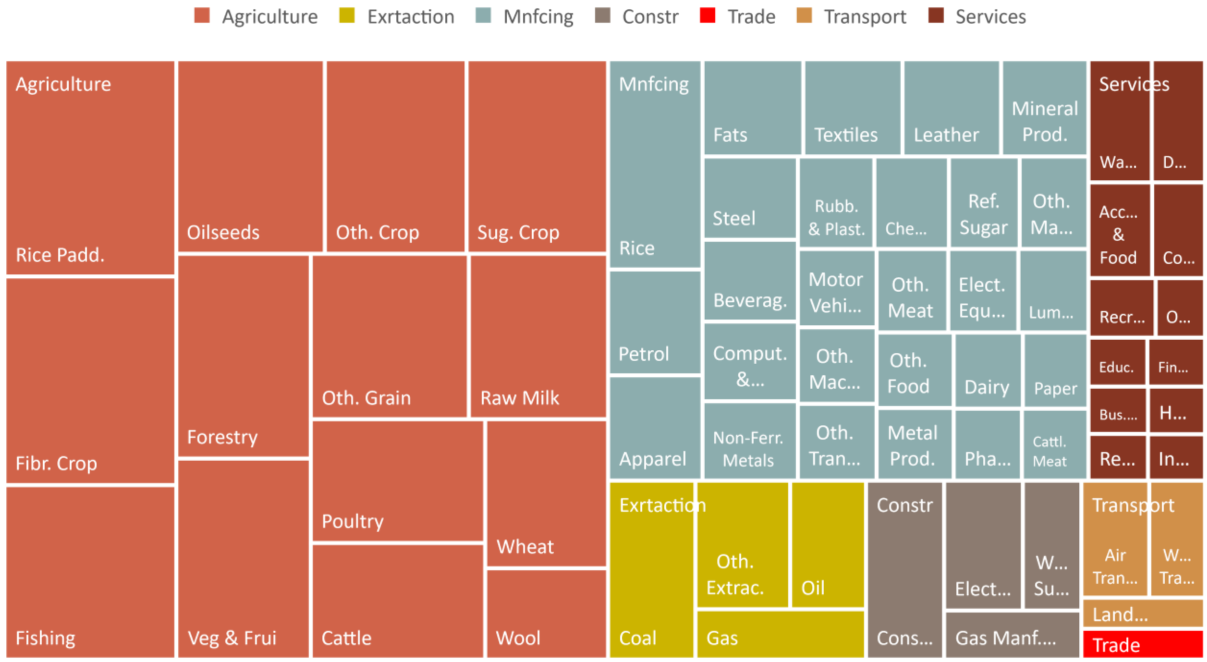


Figure 31: Contribution of individual sectors to the global decline in labor capacity.

Note: Area of each rectangle reflects the sector's contribution to the global total labor capacity loss. These are calculated as the employment-weighted average percentage decline in labor capacity loss by sector. Employment weights are from GTAP database version 10 (base year 2014).

As a result of these labor capacity losses, Cambodia and Nigeria suffer the largest annual GDP declines of more than 5% of their annuals GDPs under the 3°C warming scenario (Figure 32). Moreover, most of the countries that see the largest mean GDP losses of 4% or more (in the 3°C case) are low-income countries accounting for large portions of the world's poor: Cambodia, Nigeria, Togo, Ghana, Vietnam, Pakistan, and Bangladesh. The remainder of this paper therefore focuses on poverty in West Africa.

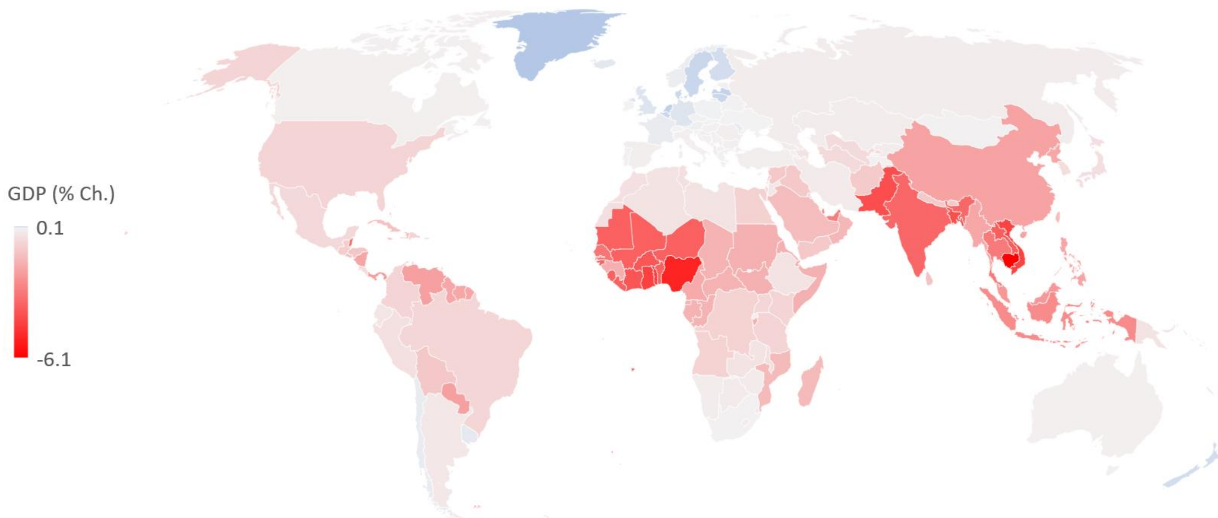


Figure 32: Country level GDP losses

4.4.2 Employment, output, and prices in West Africa

Given that heat stress and the resulting labor capacity losses are heterogenous across sectors; this alters the optimal allocation of labor across sectors within each economy. On the one hand, there is pressure for more labor to be pulled into sectors with larger labor capacity losses – as each unit of labor becomes less productive, more is needed to maintain production in response to elevated prices. On the other hand, there is also pressure for affected sectors to contract in size, reduce production, and release labor to other sectors where it is more productive. Figure 33 summarizes the re-allocation of labor across aggregated sectors that results across the seven West Africam countries we focus our poverty analysis on. Agriculture and mining, tend to see employment of labor increase more often than not across the seven countries. Labor is drawn into agriculture in Cameroon, Guinea, Nigeria, and Senegal at the expense of most other sectors. In Ghana, Burkina Faso, and Cote d'Ivoire, labor is drawn instead into mining at the expense of all other sectors including agriculture.

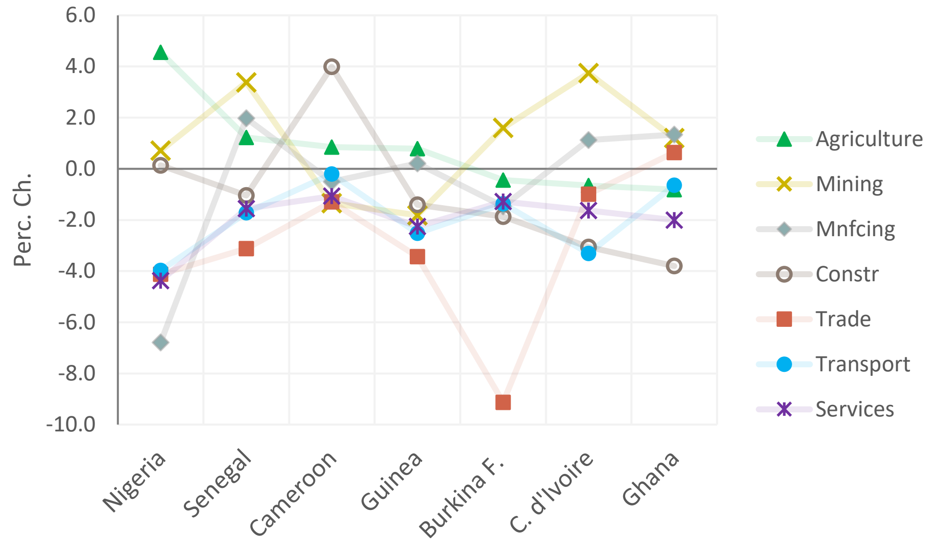
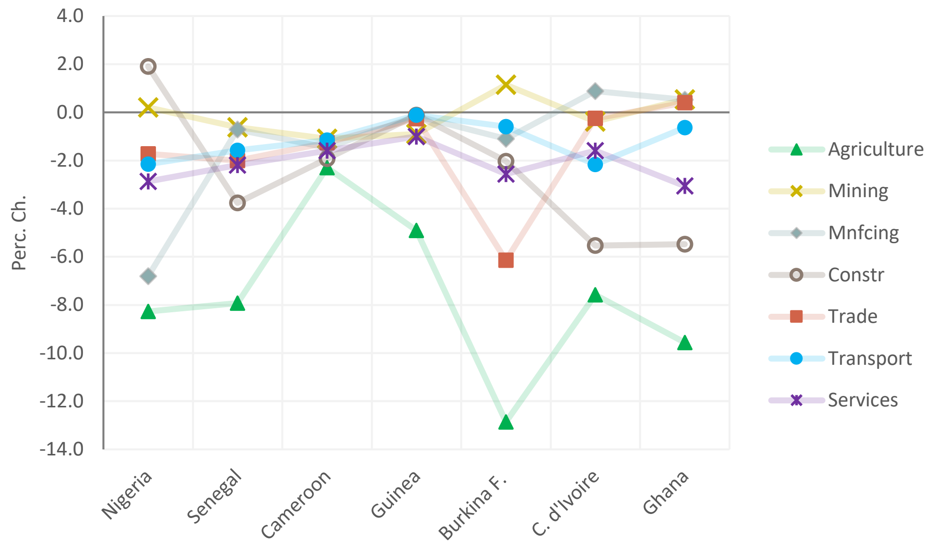


Figure 33: Employment of labor, by country and aggregate sector

The output of agriculture, on the other hand, falls consistently across all seven countries (see Figure 34). Even in country cases where labor is pulled into agriculture, this is not sufficient to prevent loss of output, but output losses are relatively smaller in these cases. The largest agricultural output losses are in Ghana and Burkina Faso of 9.6% and 12.9% respectively. The output of extraction on the other hand increases in these two countries. Nigeria also sees (small) increases in construction and extraction outputs. However, in Nigeria's case this at the expense of manufacturing in addition to agriculture.

Figure 34 also shows the corresponding price increases (in Panel B). Due to the price-inelastic nature of food demand, there are large increases in the price of agriculture in all seven countries ranging from 5% in Cameroon to over 30% in Nigeria.

A: Changes in output



B: Changes in price

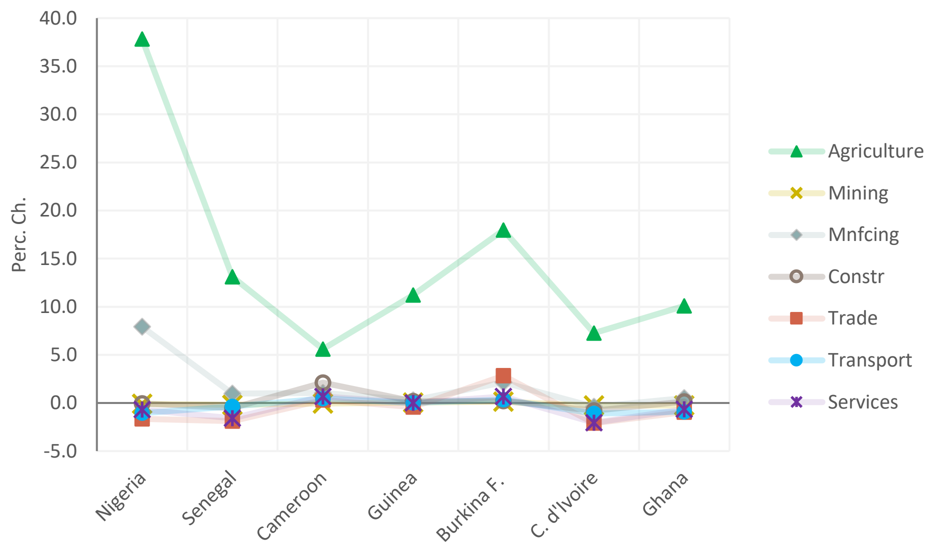


Figure 34: Impacts on output and prices, by country and aggregated sector (perc. ch.)

4.4.3 Poverty impacts across countries

As described in earlier sections, we assess poverty impacts in these seven West African countries using a household microsimulation approach. In six of the seven countries, poverty is increased as a result of heat stress induced labor capacity losses in our experiments. However, our results suggest that it is possible in some cases that poverty is reduced (or sees little change). As detailed more later, this is because labor productivity losses can in fact raise the incomes of some households as more labor is needed to maintain agricultural production and higher returns to labor are needed to induce increased employment in agriculture.

The country that sees the largest percentage increases in the poverty headcount are Nigeria and Ghana where poverty increases by 9.5% and 8.3%, respectively. See Panel A of Figure 35. The remaining countries (Senegal, Burkina Faso, Cote d'Ivoire, and Cameroon) see poverty increases of 3-5%. The exception in our sample, is Guinea, where poverty sees little change, and in fact declines by 0.1%.

Panel B of Figure 35 also shows poverty changes at the stratum level. It reveals that some household types are far more disproportionately affected: rural diverse, and non-agricultural households suffer most. In Nigeria, most of the increase in poverty can be attributed to the rural diverse and the non-agricultural strata. It is these two strata that drive approximately 70% of the country level poverty increase. In contrast, the smallest poverty increases are among households that fall under the agricultural stratum, and in the case of Guinea, poverty in the agricultural stratum declines. In the next section, the poverty changes seen in Nigeria, the largest country in the region and the one most affected, are fully decomposed and this helps highlight the household features and economic mechanisms that are behind these results.

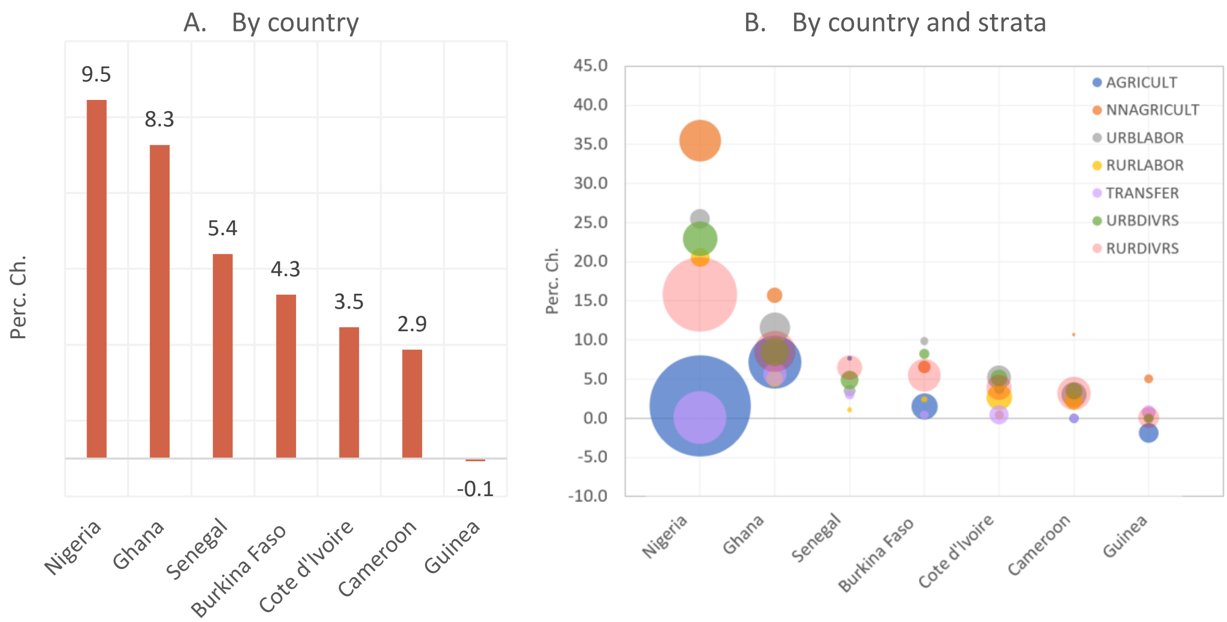


Figure 35: Changes in the poverty headcount (Percentage Change)

Notes: Bubbles in panel B represent strata where: location of bubble on the y-axis shows percentage change in poverty for the stratum and size of bubble indicates share of stratum in baseline poverty levels. Household strata are defined as follows. AGRICULT: households that earn more than 95% of their income from agricultural self-employment; NNAGRICULT: households that earn 95% of their income from non-agricultural self-employment; URBLABOR: urban households that earn 95% of their income from wage labor; RURLABOR: rural households that earn 95% of their income from wage labor; TRANSFER: households that earn 95% of their income from transfers; URBDIVRS and RURDIVRS: urban and rural households that do not fall under any other category.

4.4.4 Drivers of poverty – Nigeria as a case study

To better develop our understanding of how heat stress induced labor capacity losses drive changes in poverty, we use the case of Nigeria to fully describe how an individual country's poverty impacts are determined.

As described in the methods section, the starting point for determining poverty is changes in consumption prices and returns to factors determined by the main general equilibrium model. In Figure 36, changes in consumer prices are compared across the seven countries of focus. We see that in Nigeria, the price of "crops" increases far more sharply than the other countries.[19] This commodity group accounts for 52% of poor households' spending budget in Nigeria (not shown) and thus cost of living increases far more sharply. This increase in cost of living deflates "nominal" factor returns/income in Equation 4, pushing down real returns to all factors. Changes in real factor returns in Nigeria are summarized in Panel A of Figure 37, and in general these fall more sharply than other countries to the increased cost of living. However, it also shows that real returns to agricultural unskilled labor increase. This is the result of increased demand for this type of labor. This stems from the fact that labor capacity losses in agriculture and for unskilled workers are especially high relative to other sectors and act as a reduction in effective labor supply. Furthermore, given that agricultural production is a necessity, as each unit of labor becomes less productive, more must be drawn into the sector to dampen output losses, necessitating higher returns for agricultural labor. This increase in returns to unskilled agricultural labor therefore also occurs in other countries (not shown) [20]. In addition to returns to labor, we must also account for the fact that labor is simultaneously made less productive. Panel A of Figure 37, therefore also shows the decline in earnings caused by the direct effect of the productivity loss. In the case of agricultural labor in Nigeria, this means that despite an increase in returns (wages), total earnings nonetheless fall slightly.

Next, these wage and price changes determine changes in real incomes of the seven household types, taking into account their earnings shares (see equation 4 in the methods section). This approach accounts for the fact that e.g., changes in wages of skilled labor should play a larger role for households that earn most of their income from skilled wage employment and less of a

[19] Nigeria's underlying compensated own-price demand elasticity in smaller than in the other West African countries. This contributes towards larger price increases for crops in Nigeria.
[20] That returns/wages of agricultural labor increase as a result of heat-stress-induced productivity loss explains why in the case of Guinea, poverty falls in our results.

role for households that earn most of their income from agricultural self-employment. Panel B of Figure 37 shows the earnings shares of households near the poverty line in Nigeria. We see that the agricultural stratum earns most of its income from unskilled labor; the factor that sees its returns increase. This explains why the agricultural stratum tends to show improvements in poverty in our results: incomes for households in this stratum rise as they earn a large portion of their income from agricultural unskilled labor; the factor that experiences increasing returns. In contrast, the rural diverse stratum in Nigeria earns a significant portion of its income from capital, returns to which can be seen in Panel A to be declining by much larger margins than the increase in returns to agricultural labor.

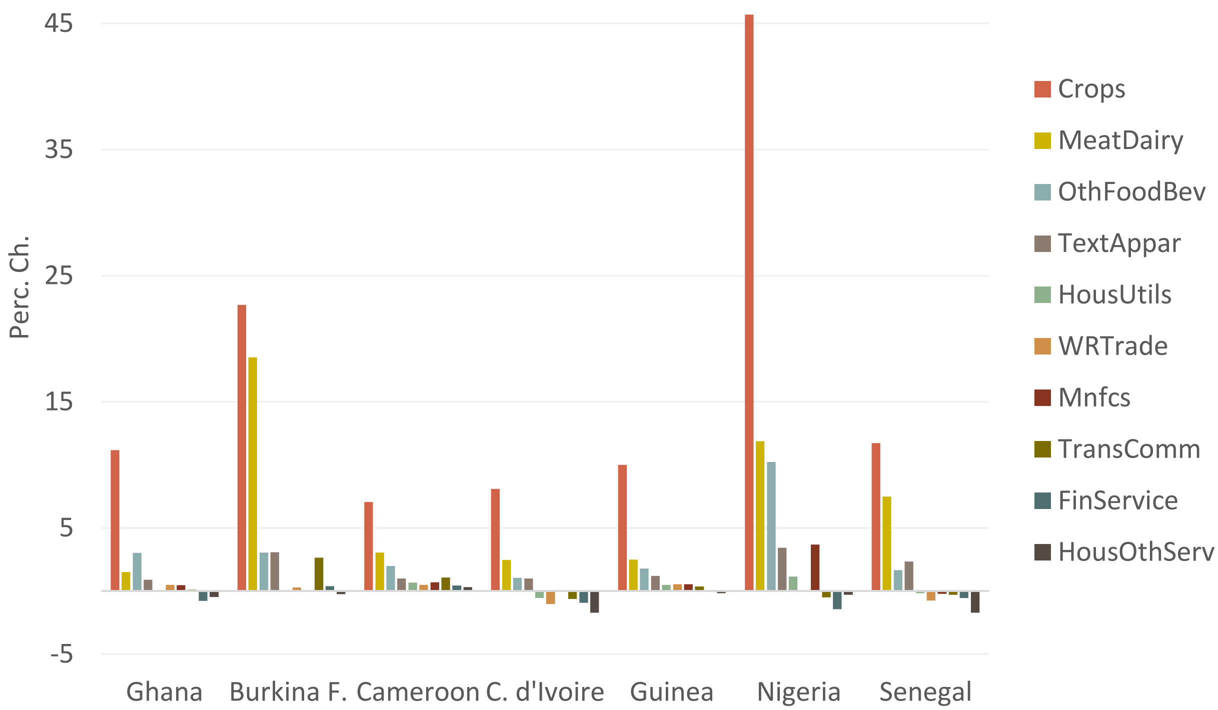


Figure 36: Changes in consumer prices, by commodity groups and country

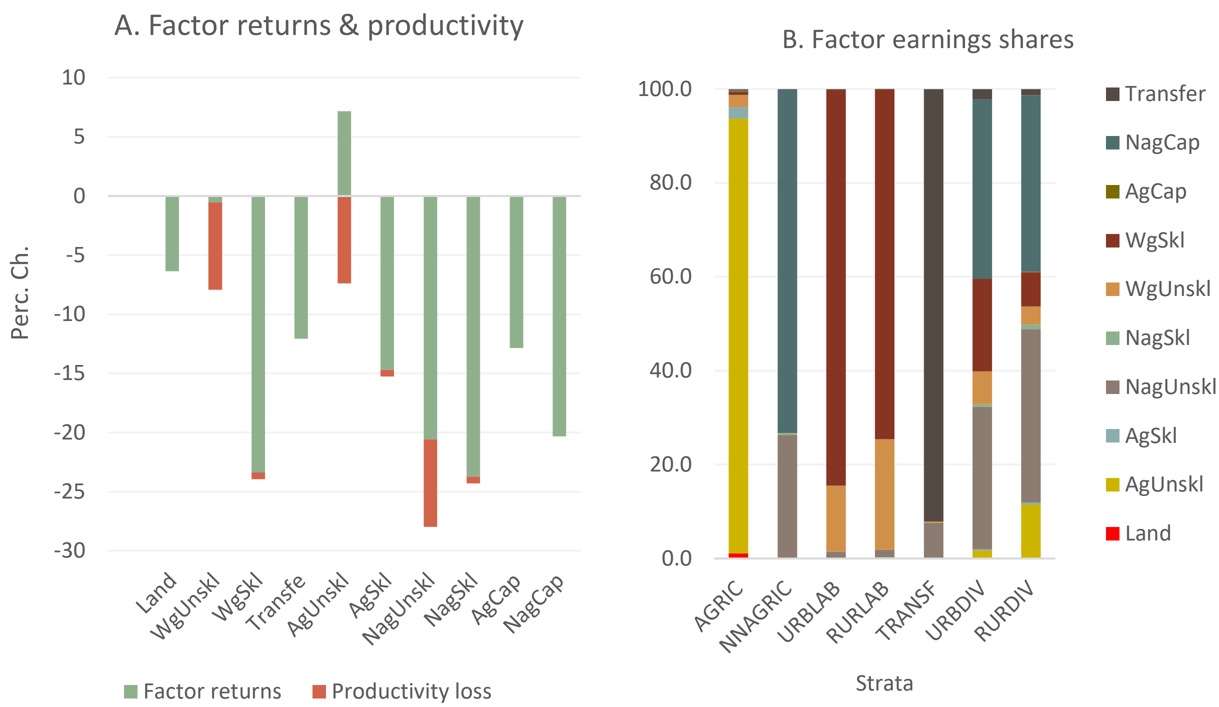


Figure 37: Factor returns and factor earnings shares by stratum in Nigeria

As a result, in Nigeria, all households near the poverty line except those that fall under the agricultural stratum see large decreases in real income. Figure 38 shows the decline in real incomes by stratum in Nigeria as well as the other six West African economies considered in the poverty analysis. It is these changes in income that we utilize in the household microsimulation. We then determine how many households fall in to (and out of) poverty as a result. The income changes shown in Figure 38 explain in large part the patterns of poverty changes reported in Figure 35: the large increases in poverty in Nigeria, for example, and the contrasting result for Guinea where poverty declines.

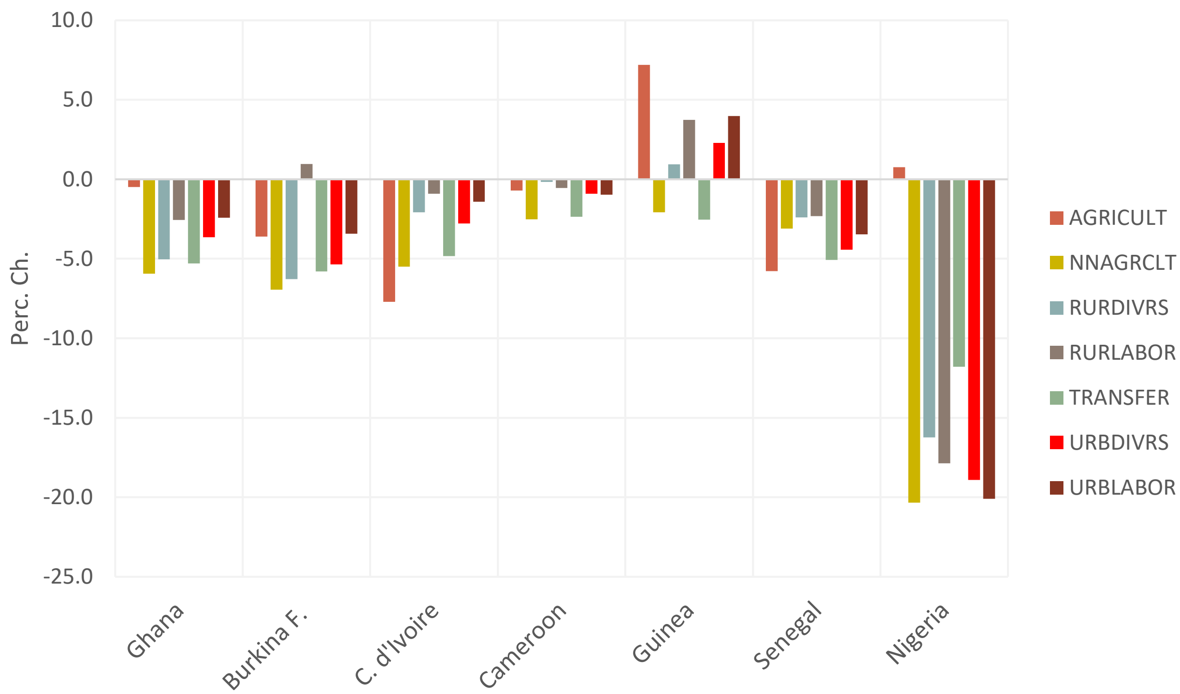


Figure 38: Real incomes near the poverty line in selected West African countries (Perc. Change).

4.5 Discussion

In this chapter, we have assessed the potential poverty consequences of heat-stress-induced labor capacity losses. At the national level, most countries considered in our poverty analysis see poverty levels increase. In our sample of seven West African countries, Nigeria and Ghana are most concerning as we see much larger percentage increases of 9.5% and 8.3% in their poverty headcounts relative to the other countries sampled. This is driven by declines in the real incomes of households near the poverty line being sharper than in the other countries and exacerbated by a large population of households near the poverty line. Other countries in our sample see more moderate poverty increases of3-5%. The exception is Guinea which experiences a slight decline in poverty.

In addition to the direct loss of earnings caused by loss of productivity, we find that the indirect impact of these labor productivity losses on relative factor returns is an important mechanism that determines the direction and magnitude of poverty headcount changes. Returns to unskilled agricultural labor can in fact increase as more labor must be drawn into agriculture to maintain food production. The returns to all other factors on the other hand are diluted. Household strata that earn significant parts of their income from agricultural self-employment can therefore see little change and even declines in poverty. Households that are diversified and rely also on other factors, land and capital, are most adversely affected in our experiments as returns to these factors tend to decline more sharply. Thus, how households that are near poverty earn their income is key in determining the extent to which a country's poverty headcount will be affected. These findings suggest that poverty-focused interventions and social safety targets should place some emphasis on the urban poor and rural diversified households.

Of course, our focus on the pecuniary impacts of heat stress abstracts from the potential health impacts and the disutility of working under such conditions. However, implicit in our labor-capacity calculations is the assumption that ISO standards for shaded rest are followed. Thus, we are in effect measuring the poverty consequences of avoiding increased mortality and adverse health outcomes. In practice, these standards are likely to be ignored in many cases resulting in severe health impacts. If these standards are violated and working hours are not reduced, then there would be additional costs associated with deteriorating health and heightened mortality. Future research should incorporate these important considerations in the economic analysis.

The broad approach underlying our results is a global static, general equilibrium experiment which imposes a future climate scenario (one of 3°C mean global warming) on the present-day economy. While we allow for adaptation through greater mechanization (capital-labor substitution), this is insufficient to prevent significant reductions in output in key sectors. The resulting GDP and output losses are most pronounced in West Africa due to its dependence on agriculture and low-skilled labor, with a large share of the labor force still employed in this sector. This comparative static approach allows us to identify the mechanisms that drive our results with relative clarity and avoids projecting what the global economy, distribution of poverty, and earnings sources might look like in a distant future when an outcome such as 3°C mean global warming might come to pass By taking a comparative static approach, we avoid the uncertainties that would be created by such projections and the economic mechanisms at play are easier to understand.

In addition to measuring poverty impacts, we also provide new assessments of wider global economic impacts at a more disaggregate level, using improved methods and data. We use more precise estimates of the WBGT for our projections of heat stress, use additional labor survey data to determine the work intensity and outdoor exposure shares of different labor types in different sectors, and our economic model disaggregates the global economy into 137 regions/countries and 65 sectors. We can therefore identify the specific countries and economic segments of the world economy that will be most impacted by human heat stress. We find that the worst affected countries in terms of country-level aggregated labor capacity losses are Bahrain, Cambodia, Pakistan, Qatar, and the UAE which lose 11 to 15% of their annual labor capacity relative to the baseline. The sector-region segments are most affected are agriculture in Cambodia, Pakistan, and Thailand. Construction is most typically the second most affected sector in Southeast Asia, South Asia, West Africa as well as the Middle East.

Finally, we note here a limitation of our economic model: as is typical with general equilibrium models, we assume that total employment does not change. Workers may shift between sectors as a result of heat stress, choosing to work more is less heat-affected sectors, such that total employment remains unchanged. However, in addition to direct loss of productivity, heat stress can have accumulated effects – such that workers working in high heat stress sectors actually leave the labor force altogether leading to a fall in total employment. Accounting for the additional loss of output due to the accumulated effects of heat stress are unaccounted for in this study (and in past studies in this area).

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APPENDIX A. SAMPLED CLIMATE MODELS

In this study, we employ the output of 10 GCMs (13 ensemble members) obtained from the CMIP6 archive for calculating WBGT (Table A1).

Table A1. CMIP6 models used in this paper

Model	**Ensemble member**
ACCESS_CM2	r1i1p1f1
BCC-CSM2-MR	r1i1p1f1
CMCC-CM2-SR5	r1i1p1f1
EC-Earth3	r1i1p1f1, r3i1p1f1, r4i1p1f1
HadGEM3-GC31-LL	r1i1p1f3
HadGEM3-GC31-MM	r1i1p1f3
MIROC6	r1i1p1f1
MPI-ESM1-2-HR	r1i1p1f1, r2i1p1f1
MPI-ESM1-2-LR	r1i1p1f1
MRI-ESM2-0	r1i1p1f1

APPENDIX B. ESTIMATION OF LABOR CAPACITY LOSSES BY LABOR TYPE AND SECTOR

Adjustment of sun-exposure shares: As described in the main text, we use data from the United States Bureau of Labor Statistics (BLS, 2020) to assign weights to labor capacity losses that are by work intensity and work conditions to produce labor capacity losses that apply to specific labor types within specific sectors and countries. This is done using equation 3 in the main model which is repeated here:

$$z_{l,a,r,g} = \sum_{i}\sum_{i} z_{r.g}^{i,c}\ \alpha_{l,a}^{c}\ \beta_{l,a}^{i}$$

The information on the α's (outdoor exposure shares) and β's (work intensity shares) in this equation are obtained from the Occupational Requirements Survey (ORS). The ORS provides job-related information related to work intensity and outdoor exposure for different occupations and economic sectors. Work intensity is described in terms such as "sedentary" to "very heavy work". We map these descriptors to specific assumption about metabolic output (e.g. we assume "very heavy work" is equivalent to metabolic output of 600W) and specific data about the proportion of work done outdoors.

However, considering that the BLS data relate to workers in the U.S., in the case of "blue-collar" labor in agriculture, we make adjustments to the sun-exposure shares (the α's) when applying these to other countries. Due to the much greater level of mechanization of agriculture, sun-exposure of blue-collar workers is likely to be much greater in lower-income countries than in the U.S. Therefore, we make the following assumptions: (i) that the sun-exposure of blue-collar workers has a logarithmic relationship to GDP per capita; (ii) the sun-exposure of blue-collar workers in Malawi is assumed to be 90% (out of the 137 countries/regions in our model, Malawi has the lowest GDP per capita, therefore we assign it the largest share). The sun-exposure share for blue-collar workers in the U.S. estimated using the BLS data is approximately 22%. Given these two data points, Panel A of the figure below shows the logarithmic curve passing through these two points, whereas Panel B shows the implied sun-exposure in a selection of low-income countries. These are the adjusted sun-exposure shares that we use to determine labor capacity losses for blue-collar workers in agriculture.

Panel A: Assumed relation between sun-exposure and GDP per capita *Panel B: Calculated sun-exposure for a selection of low-income countries*

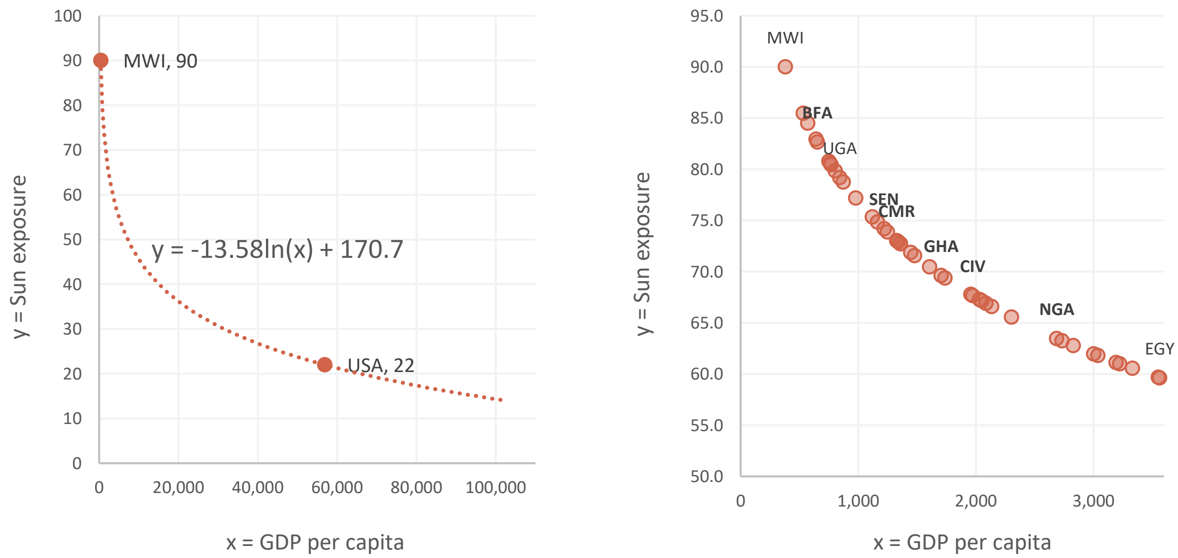


Figure B1. Adjusted region-specific sun-exposure shares for blue-collar workers ($\alpha^{c}_{l,a}$)

Aggregation over grid-cells: In order to obtain labor capacity losses that are region-specific (as opposed to grid-cell specific), we aggregate these over grid-cells as follows. This yields the final "shocks" that are subsequently introduced into our aggregate model. (i) To determine the labor productivity shocks that apply to non-agricultural GTAP sectors, we aggregate grid-cell level labor capacity losses using gridded population (pop) as weights. This assumes that within a region, non-agricultural activities follow the spatial pattern of population. (ii) To determine the labor productivity shocks that apply to agricultural GTAP sectors, we aggregate grid-cell level labor capacity losses using gridded value of crop production (val) as weights. This assumes agricultural activities within a region follow the spatial pattern of value of crop production. That is,

$$z_{l,a_1,r} = \sum_{g \in r} \frac{pop_{r,g}}{pop_r} z_{l,a_1,r,g}$$

where labor capacity losses $z_{l,a_1,r}$ obtained from the first equation are applied to non-agricultural sectors and $z_{l,a_2,r}$ obtained from the second equation are applied to agricultural sectors.

APPENDIX C. RATE AND COMPOSITION OF POVERTY IN SAMPLE WEST AFRICAN COUNTRIES

For the assessment of poverty impacts in Chapter 4, seven West African countries were sampled for the analysis of potential poverty impacts. Table and Figure C1 illustrate the variation across these countries in terms of poverty rates in the base year, and the composition of poverty in terms of household types.

Table C1: Household data sources and poverty rates in year of survey. Poverty headcount ratio are based on the $1.90 a day (2011 PPP) (% of population) poverty line as reported in the World Bank's World Development Indicators database

Country	*Household Dataset Used*	*Poverty rate in year of survey*[1]
1. Ghana	Ghana Living Standard Survey, 2017 (GLSS7)	12.7%
2. Burkina Faso	Burkina Faso Enquête Multisectorielle Continue, 2014	43.8%
3. Cameroon	Fourth Cameroon Household Survey, 2014 (ECAM4)	26.0%
4. Cote d'Ivoire	Household Standard of Living Survey, 2014 (VN2014)	29.8%
5. Guinea	Guinea Limited Poverty Assessment Survey, 2012 (ELEP 2012)	36.1%
6. Nigeria	General Household Survey, 2018	39.1%
7. Senegal	2011 Senegal Poverty Monitoring Survey (ESPS-II)	38.5%

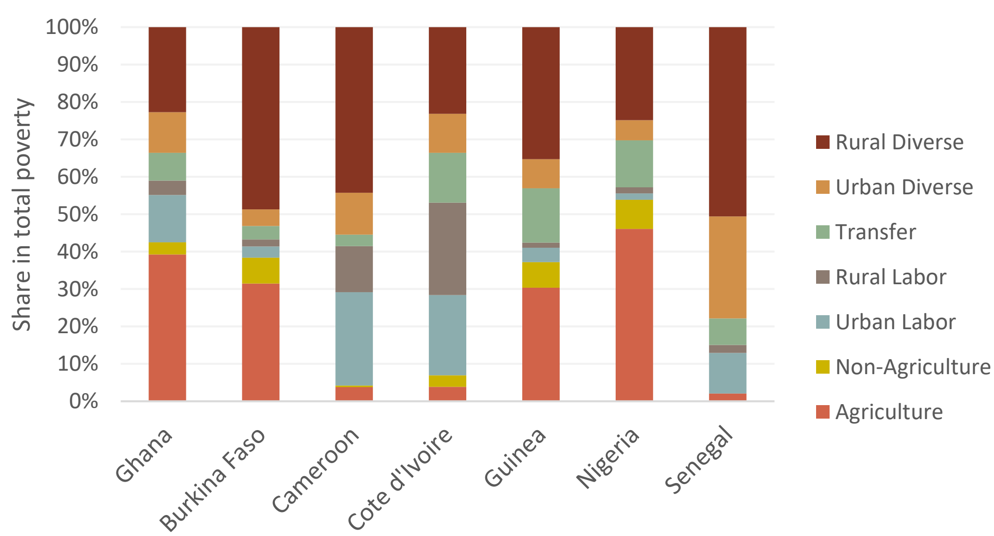
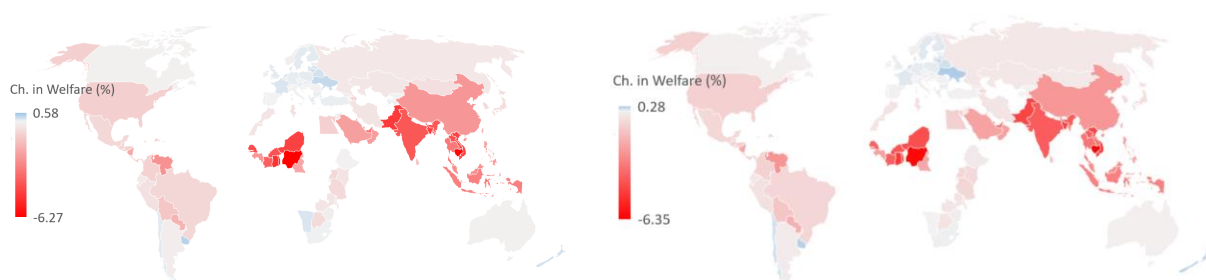


Figure C1. Share of household types in total poverty, by country

APPENDIX D. TRADE EFFECTS UNDER ALTERNATIVE TRADE ELASTICITIES

This appendix compares the terms-of-trade related results reported in Chapter 3 with results using alternative trade elasticity values. As noted in the main text, Brown (1987) found that Armington-based models, which includes the standard GTAP model, tend to over-estimate terms-of-trade effects due to the monopoly power afforded to countries due to the Armington assumption of product differentiation. For this reason, we conducted an additional set of experiments where the underlying Armington elasticities in the standard GTAP model are doubled. With these larger elasticities, terms-of-trade effects are necessarily smaller, but not to an extent that changes are broad findings or conclusions. For completeness, the key figures from Chapter 3 (using default GTAP trade elasticities) are reproduced here, along with figures using the larger (2X) trade elasticities.

Figure D1 shows that percentage changes in country-level welfare are only affected marginally. However, Figure D2 shows that the portion of this total welfare change that can be attributed to terms-of-trade effects is smaller.



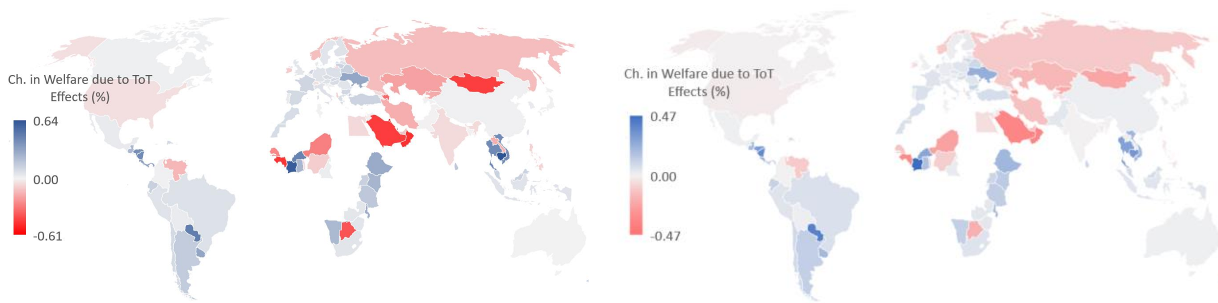
A. Using default GTAP trade elasticities

B. Using 2x GTAP trade elasticities

Figure D1. Percentage changes in country-level welfare

Figure D3 elaborates this difference further, for the nine West African countries of focus. For example, in Senegal, ToT effects account for 14% of total welfare loss if we use default GTAP elasticities. If we use trade elasticities that are twice as large, the portion of Senegal's welfare loss that is due to ToT effects in reduced to 6%. Note however that, out of our sample of nine countries, Senegal shows the largest difference – i.e., it is not necessarily the case that the percentage share of ToT effects (in total welfare) is affected to this extent by the doubling of trade elasticities. For countries with smaller ToT-related welfare changes (Cameroon, Ghana, Nigeria, and Togo), there is little change in results.

Figures D4 and D5, however, show that the underlying causes/components of ToT effects are unaffected by the magnitudes of trade elasticities.



A. Using default GTAP trade elasticities B. Using 2x GTAP trade elasticities

Figure D2. Percentage changes in country-level welfare due to terms-of-trade effects

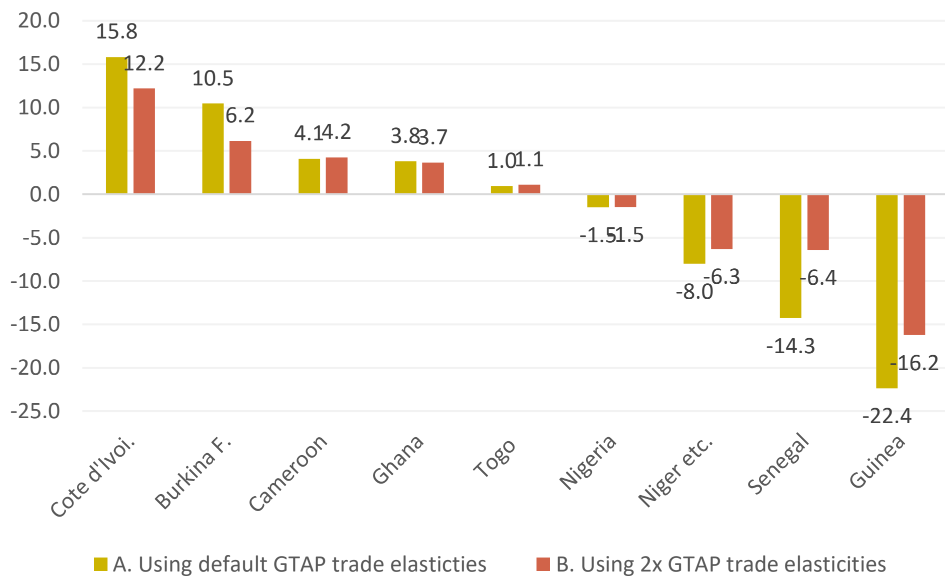
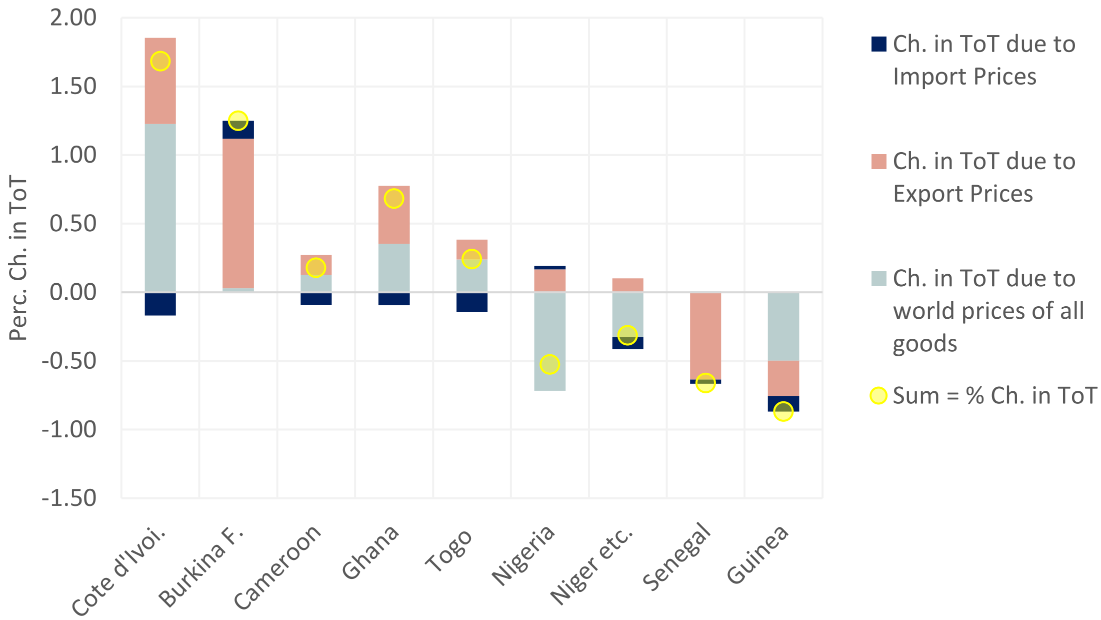
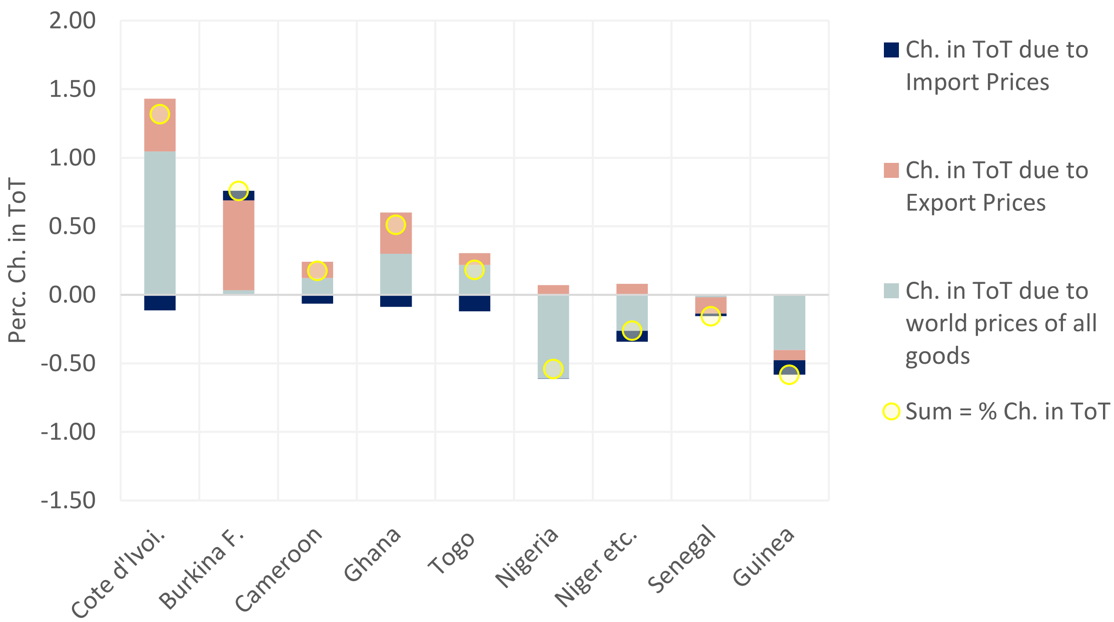


Figure D3. Percentage of total welfare change due to ToT effects, by country, under alternative elasticity assumptions

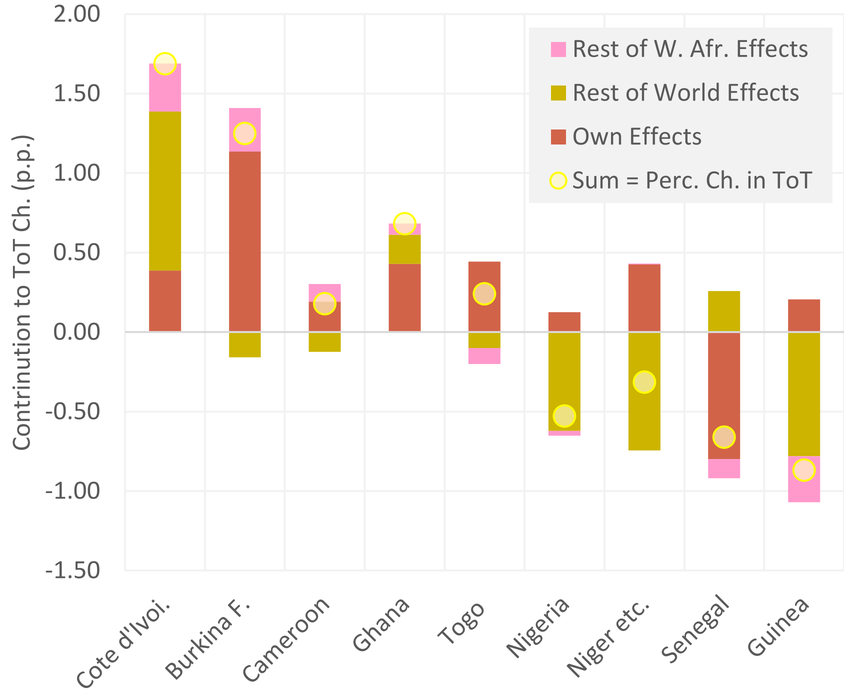


A. Using default GTAP trade elasticities

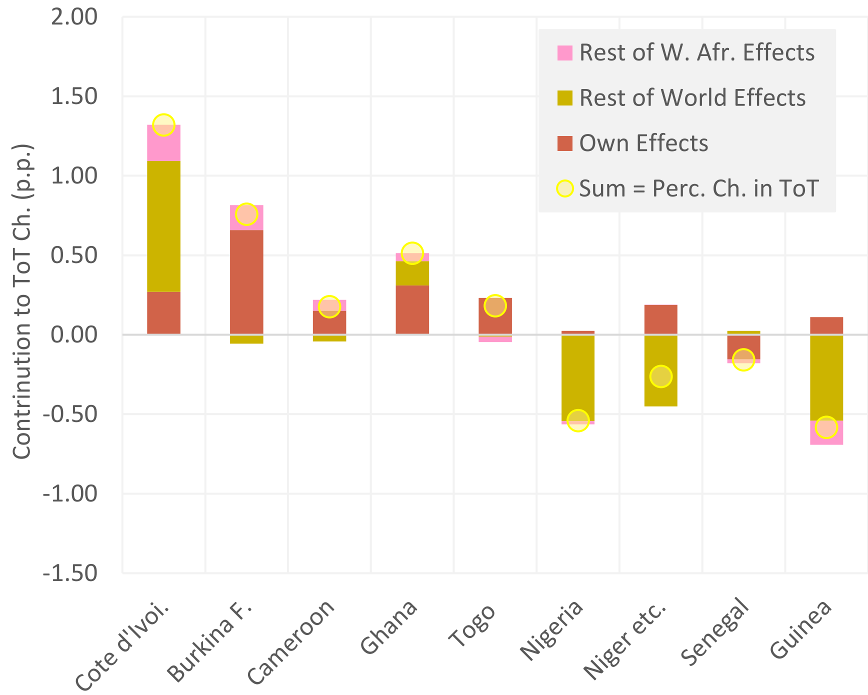


B. Using 2x GTAP trade elasticities

Figure D4. Decomposition of Terms of Trade (ToT) changes under alternative trade elasticities



A. Using default GTAP trade elasticities



B. Using 2x GTAP trade elasticities

Figure D5: Changes in Terms of Trade by country, due to heat stress labor productivity loss in (i) own country, (ii) in all other West African countries, and (iii) in all other rest of world