WORK IN PROGRESS.
PLEASE DO NOT POST OR CIRCULATE

COOL AS A CUCUMBER?
HEAT, LABOR, AND PRODUCTIVITY IN SMALLHOLDER FARMS

SUNNA HUEGEMANN & RAJSHRI JAYARAMAN

ABSTRACT

We study the impact of same-day heat on productivity and labor responses among smallholder farmers who have been contracted to grow cucumbers for an agricultural season. Harvesting is labor intensive and conducted outdoors, leaving workers exposed to heat stress under high temperatures. Using high-frequency administrative data matched to hourly weather records across dozens of villages and hundreds of farmers, we estimate the relationship between same-day temperatures and daily yields as well as earnings, and examine the mediating role of labor. We document a drop-off pattern in the contemporaneous temperature–yield relationship: yields are flat up to 33°C but decline beyond this threshold. On average, on days hotter than 33°C, farmers have 16% lower yields and earnings. We find supportive evidence that labor constraints underlie this heat penalty.

Date: March 26, 2026.

We owe a debt of gratitude to our practice partners at Marcatus, in particular Murali Sundar, Sanchitha Hanumanthappa, Kantharaj, Sunil Kombli, and Murugan. We thank Giovanna d'Adda, Peron Collins-Sowah, Friederike Lenel, Julian Röckert, and to seminar participants at the Potsdam Institute for Climate (PIK), RSERC, WZB, and the BSoE PhD conference for useful comments and suggestions. Fact-checking credit is owed to two domain experts: Armin Gerbitz for human physiology, and Brent Kaiser for plant physiology. Funding from the DFG's Collaborative Research Center TRR 190 is gratefully acknowledged.

1. INTRODUCTION

A large cross-disciplinary literature documents that high temperatures reduce agricultural productivity. Across agricultural science, climate research, and economics, studies shows pronounced yield losses at high temperatures (e.g., Lobell et al., 2011; Ortiz-Bobea, 2021; Zhu et al., 2022; Rezaei et al., 2023; Hultgren et al., 2025; Schlenker and Roberts, 2009; Burke et al., 2015; Kahn et al., 2021). This pattern is typically documented using seasonal or annual outcomes and long panels of aggregate data, which necessarily average over short-run temperature shocks. As a result, existing evidence is well suited to identifying cumulative heat effects over the crop lifecycle, but less informative about whether extreme heat imposes economically meaningful constraints at the same-day horizon.

This is material in smallholder farms, which support the livelihoods of roughly 2.5 billion people in 500 million households globally (Lowder et al., 2021). These farms are concentrated in tropical countries, which have been disproportionately affected by rising temperatures. Their labor-intensive, outdoor production systems leave them directly exposed to ambient heat on a daily basis, often with limited scope for short-run adaptation (ILO, 2019; IPCC, 2022; WHO and WMO, 2025). We know that the human body responds quickly to heat stress; see Section 2. Yet we lack evidence on whether daily heat exposure translates into contemporaneous reductions in smallholder productivity and earnings. This matters for the design of effective adaptation strategies.

This paper investigates same-day effects of heat on productivity and earnings in smallholder agriculture. Using high-frequency administrative data from hundreds of contract cucumber farmers in India matched to hourly weather records, we examine how daily heat exposure during harvest is associated with yields, earnings, and harvesting behavior. Harvesting is labor intensive and physically arduous, requiring near-daily hand-harvesting during daylight hours in direct sunlight over a concentrated harvesting period, making same-day heat exposure a potentially important constraint on productivity. The farm–day structure of the data allows us to isolate contemporaneous temperature shocks while flexibly controlling for cumulative past heat exposure and crop lifecycle dynamics. The magnitude and timing of the effects we document show that same-day heat exposure reduces smallholder yields and crop earnings by 16%. We argue that the patterns are consistent with short-run labor constraints playing a central role in shaping these contemporaneous productivity losses.

We study contract cucumber farming for the pickling export market in India. A single firm contracts smallholder farmers to grow cucumbers on a small plot within their farms for one crop season. It provides standardized inputs at cost, and purchases harvested cucumbers at contractually predetermined piece rates. Harvests occur near-daily during the harvest period, and farmers are paid based on end-of-day delivered output. This structure generates high-frequency administrative records of yields and earnings at the farm–day level, allowing daily productivity outcomes to be linked directly to realized heat exposure during harvesting. The institutional setting is particularly well suited to distinguishing contemporaneous labor responses from plant-level biological processes, as fruit weight at harvest reflects cumulative growth prior to picking, while day-to-day variation in recorded output during the harvest window is more closely linked to harvesting effort than contemporaneous plant growth.

Our analysis exploits day-to-day variation in temperature during the harvest season, using repeated observations of output and earnings for the same farmer. We outline a conceptual framework, which is grounded in science-based knowledge of physiological responses to same-day heat in humans and plants: same-day heat increases labor effort costs, but does not affect the amount of harvest-ready fruit

on the plant. The model predicts that productivity falls on hot days, operating through the intensive effort margin, and extensive (binary) labor supply margin.

We test this in the data. To capture same-day effects, we estimate specifications that compare a farmer's productivity on hotter versus cooler days within the same season, controlling for farm fixed effects, crop-week fixed effects, calendar-week fixed effects, and flexible controls for lagged heat exposure. This approach isolates short-run associations between same-day heat exposure and productivity without relying on comparisons across farms, locations, crop stages, or seasons.

We find a drop-off pattern in the heat-productivity relationship: productivity is largely unchanged at moderate temperatures but declines on hot days. When same-day daytime temperatures exceed 33°C, farmers' daily high-quality yields fall by approximately 9.6 kg, a reduction of about 16 percent relative to cooler days, with proportionate declines in earnings. These losses increase with the duration of exposure: each additional hour of extreme heat during the workday further reduces yields and earnings.

Examining labor responses, we find that hot days reduce both the likelihood that harvesting takes place, and output conditional on harvesting. Specifically, temperatures above 33°C reduce the probability that harvesting occurs by about 5.5 percentage points (7.4 percent), and reduce yields conditional on harvesting by about 8.3 kg (10 percent), with proportional declines in earnings. The former, extensive margin, accounts for about one-third of overall productivity decline and the intensive margin for the remaining two-thirds. We find little evidence of systematic postponement. or anticipation of harvests across adjacent days. Taken together, the same-day timing of these effects and the presence of behavioral responses substantially narrow the set of plausible explanations, pointing to labor constraints as a central driver of short-run productivity losses rather than cumulative plant stress. This is buttressed by heterogeneity analysis, which suggests that older age and labor scarcity mediate a sizable share of the negative heat effects.

Our findings highlight that heat exposure can constrain agricultural productivity over very short horizons, which may shape the scope for adaptation in labor intensive smallholder farming.

Related Literature. This paper contributes to a large literature studying the relationship between temperature and productivity. At the macro level, economists have documented a systematic negative relationship between high temperatures and aggregate economic productivity, using country- or region-level panels (Burke et al., 2015; Dell et al., 2012; Kahn et al., 2021). A related literature focuses on agricultural production, documenting nonlinear temperature responses for crop yields using seasonal or annual data at a regional or national level, for crops with one season-end harvest (Schlenker and Roberts, 2009; Lobell et al., 2011; Agnolucci et al., 2020; Rezaei et al., 2023; Hultgren et al., 2025; Ortiz-Bobea, 2021). We complement this work by estimating within-season, same-day heat–productivity relationships using granular micro data. This approach allows us to study short-run responses that tend to be averaged out in these studies.

A simulation-based literature has sought to quantify the contribution of labor to heat-related yield losses. This line of research operates at a macro scale, examining national or sub-national annual yields of staple crops over long time horizons, and necessarily relies on modeled rather than observed labor responses (Koteswara Rao et al., 2020; De Lima et al., 2021; Dasgupta et al., 2021, 2024; Sheng et al., 2025; Shah et al., 2025). While it highlights the potential importance of labor as a mediating

factor, it does not provide direct evidence on short-run labor responses to heat exposure. Our setting allows us to do so.

Economists have long argued that labor and effort responses constitute a plausible micro-level mechanism underlying the aggregate temperature–productivity relationship; see Heal and Park (2016) and Lai et al. (2018) for reviews. A large occupational health literature examines heat exposure in outdoor occupations, including agriculture, emphasizing physiological strain, heat illness risk, and how heat constrains safe work capacity; see Bröde et al. (2018); Flouris et al. (2018); El Khayat et al. (2022); WHO and WMO (2025), and Nath et al. (2026) for reviews. While some studies also relate heat exposure to same-day work output in agricultural labor—often in industrial or plantation settings—this evidence does not directly speak to smallholder production, where (constrained) choices are made at the household level and heat can affect outcomes through endogenous labor allocation and harvest-timing decisions.

A growing economics literature uses larger datasets and quasi-experimental variation to study heat and labor outcomes. In a seminal contribution, Graff Zivin and Neidell (2014) use U.S. time-use surveys conducted across counties and dates to show that higher temperatures reduce labor supply and increase leisure. More recently, LoPalo (2023) studies survey enumerators in the Demographic and Health Surveys and finds that workers are less productive on hotter days. These studies provide compelling evidence that heat affects labor supply and performance. We extend this line of work to a physically demanding agricultural setting where heat affects not only labor, but also plants.

In manufacturing settings Adhvaryu et al. (2020) and Somanathan et al. (2021) use factory-level production data to show that exposure to high temperatures reduces worker productivity and labor supply on the same day, with patterns consistent with human heat stress. We draw on insights from these papers while studying a setting where measured output is not mechanically pinned down by labor input alone. In agriculture, realized output can reflect both contemporaneous labor decisions and crop-related dynamics, which complicates the interpretation of same-day temperature–output relationships. We contribute evidence from smallholder harvesting that is comparable in frequency to the manufacturing studies, while confronting this additional challenge.

Finally, this paper contributes to a small but growing literature on extreme heat and smallholder livelihoods in developing countries. Existing studies document impacts on farm outcomes, household behavior, and within-season adaptation (Jagnani et al., 2021; Aragón et al., 2021; Cui and Tang, 2024; Wang et al., 2024), often using household or farm survey data measured at seasonal or annual frequency. We complement this evidence by using administrative farm-day records from a contract farming setting with fixed piece rates and near-daily harvests, which allow realized heat exposure to be linked directly to same-day harvested output and earnings. This sharper temporal alignment helps isolate contemporaneous productivity losses in labor-intensive harvesting settings.

The paper proceeds as follows. Section 2 explains the physiology of heat stress in humans and plants and Section 3 describes the study context. In Section 4 we present a simple conceptual framework. Section 5 describes our data, Section 6 our empirical model, and Section 7 our main results, with a battery of robustness checks relegated to the Appendix. We conclude in Section 8.

2. HEAT STRESS IN HUMANS AND PLANTS

This section describes what we know about acute responses to heat stress by humans and plants. The contrast between the two highlights why–physiologically–any same-day heat responses in productivity are likely to reflect worker rather than crop responses.

Humans. For the human body to function properly, internal temperature must be tightly regulated around a narrow range centered at approximately 37°C . As ambient temperatures rise, the body triggers thermoregulatory responses aimed at preventing excessive increases in core body temperature. Physiologically, humans have two main lines of defense: skin blood flow and sweating. The former transfers heat from the body's core to the periphery, but contributes to cardiovascular strain when heat exposure is prolonged or intense. The latter facilitates cooling as sweat evaporates.

In hot and humid environments, particularly under sustained physical exertion, these thermoregulatory responses may not fully succeed in offsetting heat gain. Physical exertion increases metabolic heat production, and elevated humidity limits the evaporation of sweat. When heat dissipation cannot keep pace with heat production, internal body temperature rises (Hancock et al., 2007). Empirical evidence shows that this transition happens quickly, with increasing cardiovascular strain and fatigue, even among young, healthy adults (González-Alonso et al., 1999; Vecellio et al., 2022; Wolf et al., 2022).

These considerations are especially salient in outdoor manual occupations, including labor intensive farming, where workers are directly exposed to ambient heat and cannot fully insulate themselves from environmental conditions (WHO and WMO, 2025). Occupational and public health research emphasizes that individuals can partially accommodate heat exposure through physiological regulation and behavioral responses, including self-pacing and rest, allowing work to continue under moderately hot conditions (Parsons, 2013; Dunne et al., 2013). However, this capacity for short-run adjustment is limited. Physiologically based assessments of outdoor work capacity show that as heat stress intensifies, sustained physical labor becomes increasingly constrained, reflecting limits to thermoregulation under combined heat, humidity, and metabolic load (Dunne et al., 2013; Bröde et al., 2018; WHO and WMO, 2025).

Plants. Plant responses to heat differ from human responses in two fundamental ways. First, at risk of stating the obvious, plants are sessile: they spend their adult lives fixed to one place. They cannot move to avoid heat, but instead must cope with it in situ. Second, plant responses to high temperatures operate through different physiological mechanisms. Unlike humans, plants do not maintain a centrally regulated core body temperature. Instead, heat stress in plants is mediated through local heat exchange at the leaf level, primarily via transpiration, which cools leaf surfaces but not the entire organism. Barring lethal conditions, heat stress in plants manifests in damage to key physiological functions and cellular processes, rather than through a centrally coordinated, organism-wide thermal failure (Wahid et al., 2007; Fahad et al., 2017). Cucumber varieties grown in South India by the farmers we study are adapted to warm, high-humidity environments, with optimal growth reported in the 25–35°C temperature range (Rana et al., 2017).

A central finding of the plant physiology literature is that heat effects are strongly stage-specific. Elevated temperatures are most consequential during germination, vegetative growth, flowering, pollination, and fruit set, when heat stress can disrupt fertilization, tissue growth, tissue nutrients,

and water loading, all of which reduce eventual yield (Wahid et al., 2007; Fahad et al., 2017; Jeffrey et al., 2021). This pattern also appears in the cucumber studies: El-Remaly (2023) documents heat-related damage to leaves and female flowers, with downstream consequences for fruit quality and yield under sustained summer heat stress.[1]

While extreme or prolonged heat exposure can clearly damage plants, the biological evidence indicates that plant-level yield effects predominantly reflect cumulative or lagged heat stress operating through earlier developmental stages rather than immediate responses at harvest. Consistent with this, farmers in our focus groups report that same-day losses from on-vine evaporation are minimal because cucumbers are largely shaded by foliage, with limited exposure to direct sunlight.[2]

Together, these differences between plant and human heat responses are consistent with same-day temperature exposure affecting agricultural output primarily through human labor inputs rather than through contemporaneous effects on harvest-ready fruit.

3. CONTEXT

The smallholder farms we study are located in rural South India, a region characterized by hot and humid conditions. The average total farm size is approximately two acres, and farmers cultivate cucumbers, commonly referred to as gherkins, under seasonal contracts. The average cucumber plot is about half an acre.[3] Harvest is labor intensive, with daily output largely determined by manual harvesting effort.

Economic environment. The contractor is a family-owned agribusiness with global operations, supplying major international food brands. Farmers are contracted seasonally by the company's field officers, based on client orders. Farms are selected for the agro-climatic suitability of the land to the crop. In our season of observation, they are located in 89 villages, distributed across a 7,000 km^2 area, generating within-time variation in temperatures across a relatively similar geographic region.[4]

[1]The cucumber plant biology literature focuses on stage-specific effects, documenting heat-induced changes in photosynthetic efficiency, hormone regulation, pollen viability, and floral development under sustained or repeated exposure to high temperatures (e.g. Lai et al., 2018; Yu et al., 2022; Chen et al., 2023). Humidity can also matter for cucumber physiology: Amin et al. (2021) shows that, in young cucumber plants under combined *low*-temperature and high-humidity stress, high relative humidity affects photosynthesis, transpiration, and stomatal regulation. But this evidence concerns early-stage plants under sustained stress, rather than harvest-ready fruit under short-lived hot spells. By contrast, direct evidence on acute, same-day heat effects on harvest-ready fruit is limited, and existing studies do not examine whether short-lived temperature spikes materially affect same-day fruit weight or yield.

[2]Farmers also report little noticeable same-day yield deterioration of picked fruit, since it is stored in bags, in the shade until pickup at the end of the day. This is consistent with post-harvest evidence from cucumbers showing that moisture loss is sharply reduced when protected, with covered cucumbers exhibiting less than 1% weight loss over multi-day storage horizons (Phal et al., 2013; Rodriguez Borbon et al., 2023). Given same-day harvest and pickup in our setting, together with shaded handling and the fact that the contracted cucumber varieties are heat-tolerant warm-season cultivars, post-harvest to pre-storage-related yield loss are likely to be negligible. A conservative would place it well below 1%, and plausibly below 0.5%.

[3]The remainder of their farm is used to cultivate other crops, predominantly rice and groundnuts.

[4]Ambient temperatures are a function of a number of factors including altitude, solar radiation, and atmospheric circulation (Wallace and Hobbs, 2006).

The main season starts after the last monsoon rains, and lasts until the onset of summer. During this period, in this region, rains are rare.[5]

Local factory operations are highly mechanized, but the market for factory workers is competitive. (Without regular employment in the cucumber factory, workers can easily find work in nearby garment factories.) Stable employment in its local factories requires a steady supply of cucumbers, and to maintain their "crunch", fresh produce must be pickled within a day of harvest. These two features require that the company stagger contracting, which allows comparisons across farms at different points in the crop cycle on the same calendar days.

Farmers are contracted to grow cucumbers destined solely for pickling and export. There is no domestic market for small cucumbers, that is, cornichons pickled in vinegar. As a result, unlike other horticultural crops, questions of own consumption or local market sales do not arise, eliminating output diversion. The firm provides standardized inputs to all farmers at cost, and continuous training in sustainable farming practices. Field officers visit each farm once or twice each week to supervise, monitor, and advise farmers.

The crop and harvest. Cucumbers (*Cucumis anguria* L.) are a warm-season horticultural crop. South India has some of the best agro-climatic conditions globally for this cucumber variety, which grows vertically on vines, and is well suited for pickling. The cultivars grown by the farmers are heat tolerant and thrive in direct sunlight at temperatures between 25 and 35°C. They require near-daily harvest for optimal productivity (Rana et al., 2017), making same-day harvesting decisions consequential for observed output.[6]

A crop season lasts for up to three months, from first seed to last harvest day. At different stages of the crop cycle, farmers perform different activities, beginning with soil preparation and planting seeds into well-spaced rows. Throughout the season, they conduct daily crop maintenance, including fertilization, plant support, watering, and pest management. With the possible exceptions of soil preparation prior to harvest and irrigation for those who have invested in drip systems, all tasks are done manually, by hand. See Appendix Figure A1.

The time from seed to harvest is approximately 30 days, and the harvest window lasts between 30 and 50 days, with yields following an inverted U-shaped pattern. At this stage, fruit is already mature, and daily yield primarily reflects how much fruit is harvested rather than contemporaneous plant growth. The fruit of all cucurbits, which include horticultural plants such as melons and cucumbers, need to be picked regularly, as mature fruit diverts energy from new growth. Optimally, the crop is harvested every other day during the first and last week and a half of harvest–as fruit production waxes and wanes–and every day in between, during the peak harvest period. Field officers discuss this harvesting schedule with farmers, and a pickup schedule that coincides with the optimal harvest

[5]Normal rainfall does not harm these plants. Field staff report that the main risk to heavy rainfall is flooding in black soil, due to its clay content. To minimize this risk, field officers contract farms with red soil, which has better drainage.

[6]We verify this for the seed varieties documented in internal company records. This is common practice in the region. For example, one local cucumber seed producer advertises: "Best sown in warm weather, these seeds thrive in 25–35°C temperature. Ensure well-drained, fertile soil and full sunlight."(`https://www.kailashseed.com/product-details/cucumber`)

pattern is arranged and communicated accordingly on an ongoing basis. Fruit quality deteriorates rapidly post-harvest, ruling out intertemporal shifting of harvested output.[7]

Pickup takes place at the farm gate during the day, according to the predetermined schedule date and time. Each farmer's daily produce is sorted by size; see Appendix Figure A2. There are four size categories, with the smallest cucumbers being the highest quality. High-quality cucumbers belong to the "160" grade, meaning that it takes roughly 160 fruit to make a kilogram. These fetch the highest price on the pickled cucumber consumer market. The medium-quality grade has 100 to 159 fruit per kilogram, the low-quality grade has 30 to 99 fruit per kilogram, and the largest fruit falls into the lowest-quality category. Sorting is done mechanically using grates of different sizes.

Incentives and labor. The contractually stipulated payment, common to all farmers in a given season, varies by fruit quality. Piece rates per kilogram are highest for the smallest cucumbers and fall steeply for larger fruit, creating strong incentives to harvest frequently and on schedule. The marginal reduction in piece rates between high and medium quality is 45%, between medium and low quality almost 50%, and between low and lowest quality almost 80

Fruit typically grows from one quality grade to another within one to two days. Skipping or delaying harvest is therefore costly, both in terms of current earnings and longer-term plant productivity (Rana et al., 2017). In focus groups, farmers emphasize the importance of harvesting according to the prescribed frequency.

Cucumber cultivation is a family enterprise with a gendered division of labor. Men typically perform soil preparation and pesticide spraying, while women do sowing, weeding, and lead harvesting. At the height of harvest, a well-tended half-acre plot typically requires around five full-time harvesters working seven days a week for eight to ten hours per day, implying that daily output depends on sustained physical labor input. Family members and hired labor assist in this task, with labor employed on a daily basis at a fixed local market wage. Harvesters move row by row, bending and reaching to pick fruit by hand. Larger fruit is also harvested to maintain future yields.

Harvesting involves long hours of manual labor under direct sun exposure. Daytime temperatures regularly exceed 30°C, and relative humidity is persistently high during the harvest season, typically in the range of about 60–70%. Work is performed outdoors for much of the day, constraining short-run behavioral adaptation to heat exposure.

4. Conceptual framework

This section sketches a simple model to conceptualize how same-day heat exposure can affect harvested output in a setting where fruit harvest-readiness is predetermined on the day of scheduled harvest and harvesting is labor intensive.

Consider a farm i on a scheduled pickup day t. Let $R_{it} \geq 0$ denote the amount of harvest-ready fruit available at the start of that day.[8] This captures what we know about the plant's physiology: fruit

[7]Similar constraints hold for other labor-intensive horticultural crops; for example, Jayaraman et al. (2016) describe how tea plant growth and harvesting practices limit the scope for shifting harvested output across days.

[8]We abstract from the intertemporal evolution of R_{it} in the model. In the empirical analysis, slow-moving biological and calendar effects are absorbed by farm fixed effects, crop- and calendar-week fixed effects, and controls for lagged heat exposure.

weight at harvest primarily reflects cumulative growth prior to picking, and short-lived same-day temperature fluctuations are unlikely to materially alter the stock of harvest-ready fruit.

Output is the fraction of available harvest that is picked and depends on labor effort. Let $e_{it} \geq 0$ denote harvesting effort, measured in efficiency units of labor input. Output is given by

$$y_{it} = R_{it}\,\theta(e_{it}),$$

where $\theta(e) \in [0,1]$ is weakly increasing and differentiable at any interior effort level $e^* > 0$, with $\theta'(e^*) > 0$. Let H_t denote same-day heat exposure. Same-day heat affects harvesting via the cost of effort. Conditional on harvesting, the farm chooses effort to solve

$$\max_{e_{it} \geq 0} \; p\,R_{it}\,\theta(e_{it}) - C(e_{it}; H_t) - F,$$

where $p > 0$ is the contractually fixed piece rate and $F \geq 0$ is a reduced-form fixed cost of organizing harvesting on that day. We normalize $C(0; H) = 0$ for all H and assume

$$C_e(e; H) > 0, \quad C_{ee}(e; H) > 0, \quad C_{eH}(e; H) > 0.$$

The first two assumptions ensure convex effort costs. The last captures the central idea from human physiology: heat increases the marginal cost of effort.

Let $e^*_{it}(H_t)$ denote the optimal effort choice when harvesting occurs. We impose the usual second-order condition that, at any interior optimum,

$$pR_{it}\theta''(e^*_{it}) - C_{ee}(e^*_{it}; H_t) < 0,$$

so that the first-order condition characterizes a local maximum.

Define the indirect value of harvesting as

$$V(R_{it}, H_t) \equiv \max_{e_{it} \geq 0} \; p\,R_{it}\,\theta(e_{it}) - C(e_{it}; H_t) - F.$$

The work decision is

$$W_{it} = 1 \iff V(R_{it}, H_t) \geq 0.$$

The model generates two empirical predictions. (See Appendix B for proofs.)

PROPOSITION **1.** *Holding the amount of harvest-ready fruit fixed, higher same-day heat exposure weakly reduces harvested output on days when harvesting occurs.*

The intensive margin follows from the first-order condition for optimal effort: heat raises the marginal cost of effort and therefore reduces optimal effort, which lowers harvested output.

PROPOSITION **2.** *Higher same-day heat exposure reduces the likelihood that harvesting occurs on a scheduled pickup day.*

The extensive margin follows from the envelope theorem: since higher heat raises the cost of any positive effort, it weakly reduces the indirect value of harvesting, making harvesting less likely.

Taken together, Propositions 1 and 2 imply that same-day heat exposure reduces harvested output. In the model, this overall heat penalty operates entirely through labor: same-day heat affects the probability of harvesting and the intensity of effort when harvesting occurs, while the within-day stock of harvest-ready fruit is taken as fixed. The empirical analysis evaluates whether this

labor-based mechanism is consistent with the data, and whether short-run intertemporal substitution mitigates these effects.

5. DATA

In this section, we describe data sources and data construction, and descriptive statistics for our main panel of farmers, who are observed for a single harvest season, from December 2023 to May 2024.

1. **Data Sources.** We use three data sources: weather data for temperatures, administrative data for farming outcomes, and survey data for farm(er) characteristics.

1.1. *Company records.* We digitize two types of company records. The first tracks the daily output of each farmer, namely, how many kilograms of cucumber were harvested in each quality grade. The second contains consolidated balances for each farmer which, in addition to the farmer's seasonal harvest revenues and input costs, include several features that facilitate our analysis. First, the date of sowing allows us to mark the start of the farmer's crop cycle, permitting us to control the crop stage. Second, the records report the seasonal piece-rate schedule. By combining piece rates with daily output, we are able to construct daily crop earnings. Third, village names and farmer IDs were used by field staff in branch offices to geolocate each farmer's village. Finally, the records include each farmer's cucumber plot size, which we use together with daily output to calculate daily yields.

1.2. *Weather data.* We obtain hourly ERA5 weather data from the Copernicus Climate Change Service, accessed via the Climate Data Store. ERA5 provides comprehensive reanalysis data at a high level of temporal and geographic disaggregation. We use hourly 2m temperature, available on a $0.25^\circ \times 0.25^\circ$ grid, corresponding to a spatial resolution of approximately 28 km by 25 km at this latitude.[9]

We match hourly temperature data to administrative records using village identifiers and dates. This allows us to construct a village-level hourly temperature time series for each of the 89 study villages by spatially interpolating the gridded data. Specifically, for each village and hour, temperature is computed as an inverse-distance–weighted average of the four nearest grid points.

Figure 1 presents the spatial distribution of study villages within South India, overlaid with the 0.25° temperature grids. Villages are located within a relatively compact geographic region but experience meaningful variation in hourly and daily temperature over time.

Since harvest takes place during daylight hours and high temperatures are a daytime event, we restrict attention to hourly temperatures between 6 a.m. and 6 p.m. We use these data to construct daily measures of temperature exposure, including daily maximum temperature and the number of hours per day above relevant temperature thresholds. These measures capture both peak heat exposure and the intensity and duration of heat within a day.

[9]We use dry-bulb temperature rather than composite heat stress indices (e.g., wet-bulb temperature or WBGT) to minimize measurement error, as these indices compound uncertainty across multiple weather variables. With consistently high humidity (60–70%) in our region, temperature variation is the primary driver of daily heat exposure.

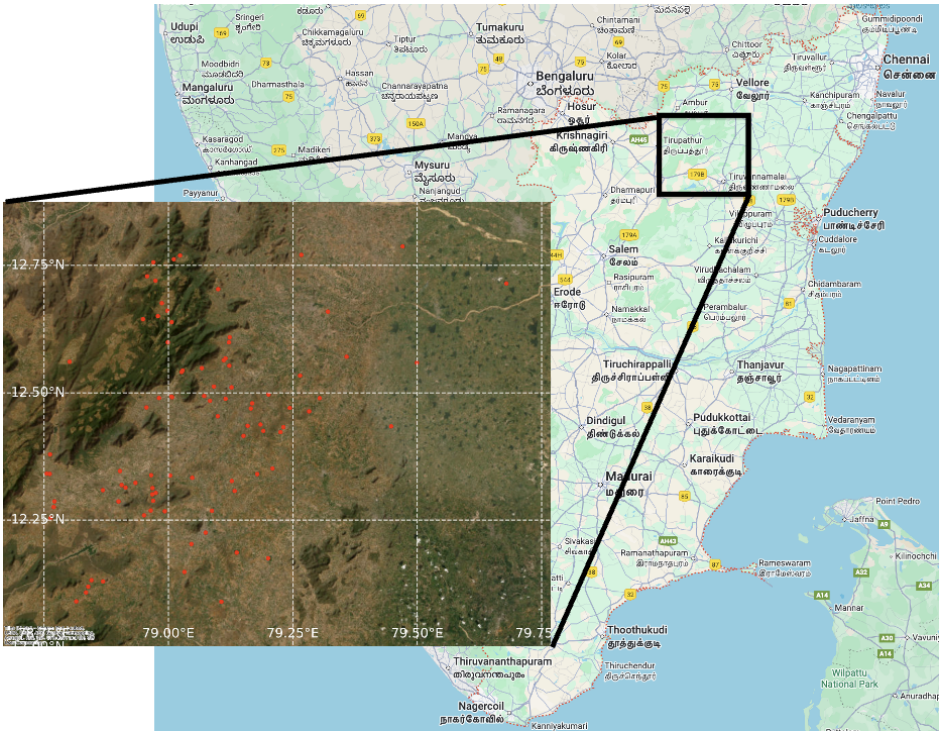


FIGURE 1. Study villages and temperature grids

1.3. *Survey data.* A baseline survey was administered in person, during the crop season, by trained field officers to contract farmers. The respondent was the household member with primary responsibility for cultivating cucumbers. The survey collected information on farmer and household characteristics, including gender, age, cucumber cultivation experience, and difficulty in hiring labor during harvest. We use these characteristics to explore heterogeneous responses to heat exposure.

2. **Sample construction.** In the 2023-24 season the firm contracted a total of 666 farmers, with instructions and incentives to "focus" on harvesting high-quality fruit.[10] We exclude two farmers who had no subsequent harvest records, one farmer whose geolocation could not be verified, and nine farmers whose yields were outliers (defined as exceeding ±3 standard deviations of the mean). This leaves a final sample of 654 farmers.

For each farmer, we use the recorded sowing date to restrict the analysis to days 30–100 of the crop cycle, corresponding to the period during which harvesting should occur. This restriction ensures that observations are drawn from comparable stages of the crop lifecycle. Harvest occurs, and is recorded, only on pickup days, we further restrict attention to scheduled pickup dates.

Harvest is measured in kilograms for each farmer on each scheduled pickup day. Missing values arise either because no pickup occurred, or because the farmer did not harvest on that day. On days when pickup was scheduled in the farmer's village but no harvest is recorded, we treat missing values as

[10]A further 40 farmers were instructed to focus on lower-quality fruit. We exclude these farmers because their incentives, harvest practices, and yield profiles differ fundamentally.

true zeros. Daily yields, our primary outcome variable, are constructed by dividing output in each quality grade by farm size. Daily earnings, our secondary outcome of interest, are constructed by multiplying grade-wise output by the corresponding piece rate.

3. **Descriptive statistics.** Table **??** reports summary statistics for the main variables used in the analysis. The farmer–harvest day panel comprises 27,867 farm-day observations covering 654 farms over 115 harvest days, located in 89 villages, matched to a weather panel containing 3,168 village-day observations.

Farmers have an average age of 40, and 44% are female. They operate small cucumber plots averaging just under half an acre and have, on average, just under three prior seasons of experience cultivating cucumbers. Labor scarcity is common, with about two-thirds of farmers reporting difficulty hiring labor during harvest.

The harvest period is short but intense. In keeping with cropping patterns for this cucumber variety, it lasts just under seven weeks, with scheduled pickups arranged for 30 harvest days on average. Farmers harvested on approximately 70% of these scheduled days.

Yields and earnings exhibit substantial dispersion across farmers. Average daily yields are 56 kg per acre for high-quality fruit and 112 kg per acre for total yield. Daily earnings average approximately INR 3,400 (roughly €20 or USD 22).

Heat exposure during harvest is common. Average daytime temperatures are close to 28°C, but daily maximum temperatures frequently exceed 30°C and farmers experience nontrivial exposure to temperatures above 33°C. Since heat stress depends on both intensity and duration, we use measures capturing both in the analysis.

TABLE 1. Summary Statistics

Number of farmer-harvest day observations	27,867
Number of farmers	654
Number of harvest days	115
Number of villages	89
Number of village-harvest day observations	3,168

	N	Mean	Std. Dev.	Min	Max
Individual					
Age	654	39.1	10.3	15	70
Female	654	0.44	0.50	0	1
Farms					
Gherkin plot size	654	0.48	0.23	0.10	1.60
Farmer's experience (seasons)	654	2.64	1.95	0	10
Labor scarcity	642	0.65	0.48	0	1
Harvest					
Length of harvest period	654	47.7	12.2	2	78
No. harvest days	654	30.0	9.07	2	48
Any harvest on pickup days	27,867	0.70	0.46	0	1
Yield					
Daily High-quality yield (kg/acre)	27,867	55.9	60.9	0	804
Daily total yield (kg/acre)	27,867	111.8	127.1	0	1780
Earnings					
Daily earnings/acre	27,867	3397.4	3606.0	0	49380
Daily earnings	27,867	1562.2	1792.7	0	24690
Weather					
Avg. daytime temperature	115	28.0	2.63	23.1	33.9
Maximum temperature	115	31.4	3.17	23.9	38.5
No. hours above 33°C	115	1.84	2.88	0	8.60

Notes: This table presents summary statistics for the main variables used in the analysis. The sample includes 654 farmers across 89 villages observed over 115 harvest days during the 2023-2024 cucumber season, generating 27,867 farmer-harvest day observations and 3,168 village-harvest day observations. Individual characteristics include farmer age, gender, prior experience growing cucumbers (measured in number of seasons), and self-reported difficulty hiring labor during harvest. Farm characteristics include cucumber plot size in acres. Harvest variables describe the length of the harvest period (days from first to last harvest), the number of scheduled pickup days, and the rate at which farmers actually harvested on scheduled pickup days. Yield is measured in kg/acre for high-quality fruit (smallest size grade) and total yield across all quality grades. Daily earnings are calculated by multiplying grade-specific output by contractually predetermined piece rates. Weather variables are constructed from hourly ERA5 data matched to village locations. Average daytime temperature is the mean temperature between 6 a.m. and 6 p.m. Maximum temperature is the daily maximum during daylight hours. Hours above 33°C count the number of daylight hours when temperature exceeds this threshold.

6. Empirical Strategy

In this section, we describe the main threats to identification of same-day heat effects on productivity, and explain how we address them in our empirical model. We also outline our strategy for building supportive evidence that labor responses are likely to play a central role in same-day heat effects.

1. **Identification.** We face three main threats to identification. The first is unobserved farm heterogeneity. Farms may be systematically different in terms of farm location (e.g., altitude or local labor market conditions) or farmer quality (e.g., skill or experience). These, in turn, may be correlated with temperatures and yields. For example, temperatures may be hotter at lower altitudes, and casual labor markets may be tighter, resulting in downward biased estimates of heat effects on productivity. To address (time invariant) unobserved heterogeneity, we include farm fixed effects (FE).

The second challenge is spurious negative correlation between temperatures and yields. Temperatures rise steadily through the season, while yields follow a classic inverse-U shaped harvest pattern reflecting crop maturity. This is evident in Figure 2, which shows how average yield evolves over the crop lifecycle (Panel 2a) and temperatures evolve over time (Panel 2b). In our model, crop-week FE accounts for the crop age, and calendar-week FEs account for secular changes in seasonal temperature. Separate identification of these is feasible due to staggered sowing across farms.

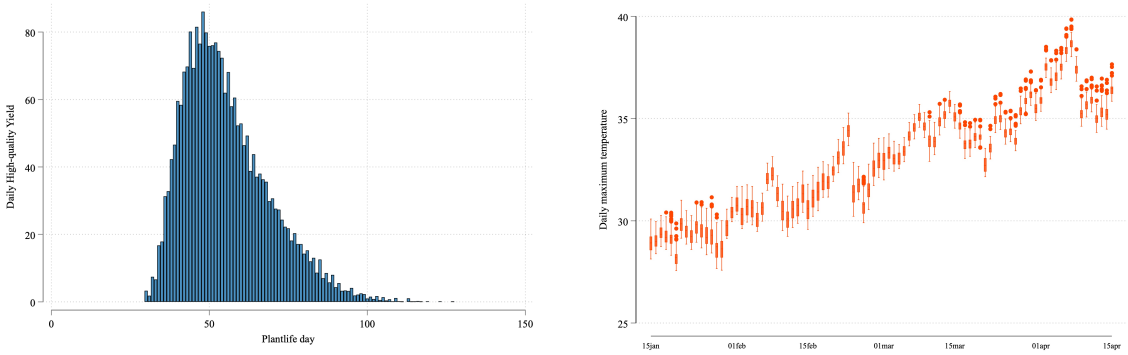
Finally, because temperature is serially correlated, contemporaneous heat may capture lagged or cumulative effects of heat exposure on both plants and workers. We therefore control flexibly for recent heat exposure by including heat on the previous day, and aggregate heat exposure over the six preceding days. For plants, past heat exposure may affect productivity through cumulative stress at earlier developmental stages. For workers, lagged heat may influence labor supply through short-run behavioral responses, including intertemporal substitution of harvesting effort across nearby days. In particular, if a previous day is unusually hot, farmers may defer harvesting to the following day, whereas sustained heat over multiple days is likely to reduce overall labor input. We do not attempt to map specific lag lengths to distinct physiological channels. Instead, by controlling for recent heat exposure, we net out cumulative and intertemporal effects to more credibly isolate the same-day effect.

2. **Same-day threshold effects.** We estimate variants of the following model to investigate the relationship between same-day temperatures and cucumber yield:

$$y_{iv,t} = f(\text{Temp}_{v,t}) + \alpha_i + \kappa_{s(i),t} + \omega_t + \delta_{d(t)} + \varepsilon_{iv,t} \tag{1}$$

where y_{ivt} denotes the high-quality yield of farm i, which is located in village v, on calendar date t. The model includes individual FE α_i; crop-week FE $\kappa_s(i), t$, which varies by farmer i's sowing date s_i, and calendar time t; and calendar-week FE are ω_t. In addition, FEs δ for the day of the week $d(t)$ account for weekly regularities in harvest patterns (e.g., weekends off).

The object of interest is $f(\text{Temp}_{vt})$, which describes how the same-temperature in village v affects outcomes. In the absence of previous estimates on contemporaneous effects of heat, we begin with a flexible specification for $f(\cdot)$, estimated using a natural cubic spline with varying degrees of freedom, following Ortiz-Bobea (2021). And since we record 12 hours of temperature per day, we allow



(A) Yield over crop cycle

(B) Temperature over calendar time

FIGURE 2. Crop cycle and temperatures *Notes.* This figure depicts average yields over the crop cycle (Panel a) and daily ambient temperatures over the harvest season i.e. calendar time (Panel b).

for flexible measures of same-day exposure to the full range of daytime temperatures, and daily maximum temperatures and degree-hours (i.e., the number of hours in a day at various temperatures).

Crucially, we use flexible specifications to determine whether our estimates are consistent with patterns predicted by the physiology of human heat stress, namely, productivity being unchanged over a range of same-day temperatures, but then decreasing when they exceed a heat threshold. We begin by estimating model (1) without controlling for past heat. However, after identifying a threshold, capture past heat exposure through dummy variables ($D_{v,t}$) equal to 1 on days this threshold is exceeded.

3. **Same-day heat penalty.** Using the threshold uncovered in the first exercise, we estimate a parametric model to estimate a "heat penalty" by asking, "What happens to outcomes when same-day temperatures exceed the daily heat threshold?" Concretely, we estimate the following variant of model (1):

$$y_{iv,t} = \beta H_{vt} + \gamma D_{v,t-1} + \phi \sum_{k=2}^{7} D_{v,t-k} + \alpha_i + \kappa_{s(i),t} + \omega_t + \delta_{d(t)} + \varepsilon_{iv,t} \tag{2}$$

There are two differences between model (1) and model (2). First, we impose a linear functional on $f(\cdot)$. Second, we use a daily aggregate measure of exposure to temperatures that exceed the heat threshold. Concretely, $f(\text{Temp}_{vt}) = \beta H_{vt}$, where H_{vt} measures daily heat exposure and β is the same-day "heat penalty": the effect of heat exposure on yields. In our main specification, heat exposure is captured through the dummy variable D_{vt} as defined in equation (2), so β captures the average effect of (any) same heat exposure. We also measure hours of daily heat exposure ("heat-hours") to temperatures exceeding the threshold, in which case β captures the marginal effect of an additional hour of heat exposure.

4. **Labor responses.** In a final step, we explore labor responses to heat exposure. First, using model (2), we estimate labor supply responses along the extensive margin asking whether farmers have any

harvest (i.e. have any labor input) on heat-days. We also investigate the intensive margin, by condition productivity on harvesting. Second, we examine whether farmers engage in intertemporal substitution of labor by investigating the effects of yesterday's and tomorrow's heat on today's productivity. If farmers anticipate hot weather, they may harvest more heavily the day before; conversely, if they skip or reduce harvesting on a hot day, they may compensate by harvesting more intensively the following day to catch up on fruit that has continued to ripen. Evidence of such delayed or anticipatory responses would suggest that heat-induced losses can be partially offset through re-timing of effort. Lastly, we estimate heterogeneous responses to same-day heat by interacting the heat-day dummy variable with farmer gender, experience, age, and whether they have hiring difficulties. There is no biological foundation for women experiencing more heat stress than men. The plant is not affected by same-day exposure, and farmer experience with cucumber cropping is unlikely to help manage human heat stress. By contrast, age is a well-established risk factor, and the presence of hiring difficulties is likely associated with fewer available harvesters and higher risk of heat stress on heat-days.

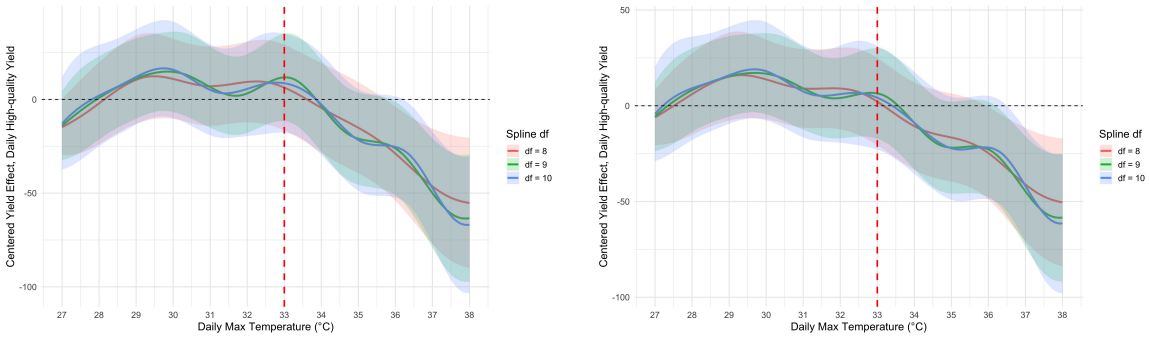
7. Main results

This section discusses our main results. We begin by presenting estimates for the semi-parametric relationship between same-day temperatures and yields described in model 1, and then quantify the same-day heat penalty, by estimating β from model 2. We conclude by exploring labor responses to heat exposure.

1. **Threshold effects.** Figure 3 depicts the relationship between maximum same-day temperature and high-quality yield, estimated using semi-parametric natural cubic splines of degree 8, 9 and 10. The pattern in Panel A3a, which does not control for past heat but does all other FE, is consistent with well-documented patterns of humans' physiological response to heat stress. Estimates are imprecise, but yields are relatively flat until 33°C, after which they decline linearly with temperatures. This is consistent with a threshold effect at 33°C. This threshold lies before the 35°C upper bound of optimal ambient temperature for cucumbers (Rana et al., 2017). In the 60–70% relative humidity range characteristic of the region, this threshold corresponds to a WBGT of approximately 29–30°C. This range closely aligns with experimentally identified thresholds for human heat stress (Vecellio et al., 2022, 2023). Together, this evidence is consistent with threshold effects characterizing same-day human heat stress.

In Panel A3b we use this threshold to control for past heat. Doing so tightens confidence bands and smooths the temperature-yield response function. Still, after a 33°C temperature, the effect of heat on productivity becomes significantly negative. Patterns are similar when we measure exposure in degree-hours rather than daily maximum temperature; see Appendix Figure A3. Similar patterns emerge when we use indicator variables for different maximum-temperature bins (Figure 4).

Next, we use the 33°C threshold estimate to quantify the same-day heat penalty, in terms of yields, as well as crop earnings. Table 2 presents the results of this exercise. In separate regressions, heat exposure is measured by whether daily maximum temperature exceeds 33°C (Panel A), and the number of hours above this threshold (Panel B). All specifications include farmer, plant-week, calendar-week, and day-of-the-week fixed effects. Columns 2 and 4 add controls for yesterday's heat and cumulative heat over the previous six days.



(A) Without past heat controls (B) With past heat controls

FIGURE 3. Threshold effects of same-day maximum temperature on high-quality yield *Notes.* This figure depicts the relationship between same-day maximum-temperature exposure (Panel (A)), and daily high-quality yields. Functions are estimated using a natural cubic spline

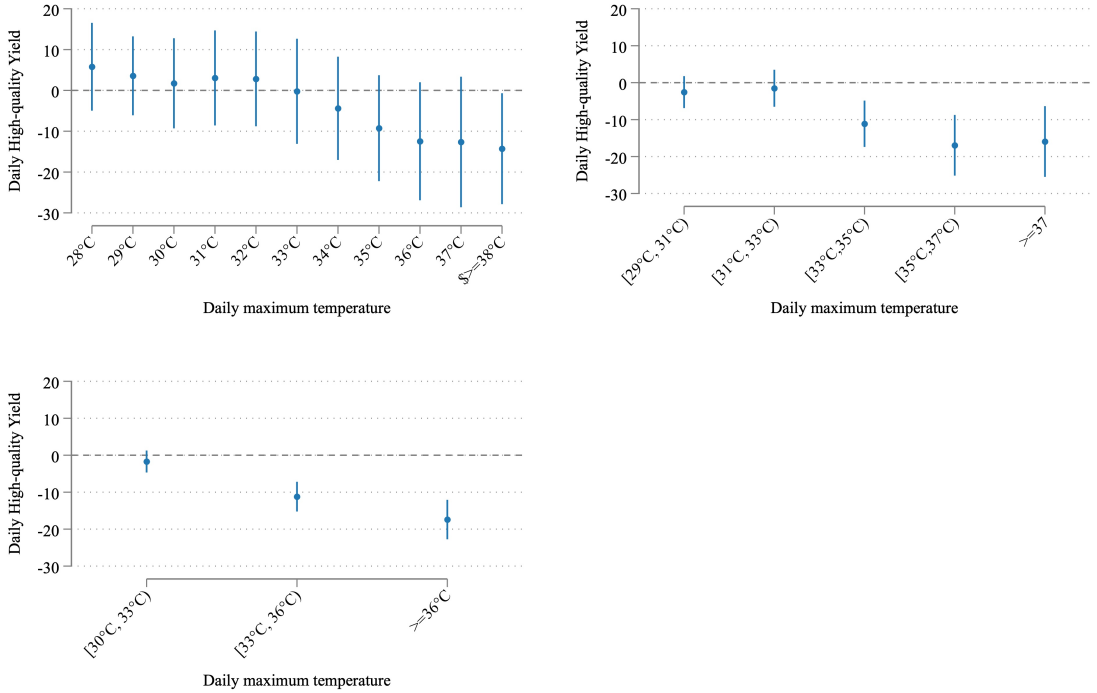


FIGURE 4. Dummy variable specification. *Notes.* This figure depicts coefficient estimates for binary indicators in three separate regressions with the full set of controls. Clockwise from top left, the indicators are for 1-, 2-, and 3-degree Celsius daily maximum temperature bins.

TABLE 2. Effects of Extreme Heat on Daily Yield Outcomes

	Daily High-Quality Yield		Daily Earnings per Acre	
	(1)	(2)	(3)	(4)
Panel A. Maximum temperature				
Max. temperature > 33°C	-9.618***	-9.656***	-661.5***	-646.8***
	(1.618)	(1.531)	(87.09)	(83.33)
Panel B. Duration of heat				
Each additional hour > 33°C	-2.384***	-1.986***	-168.6***	-131.4***
	(0.502)	(0.506)	(31.83)	(30.77)
Baseline mean	60.38	60.38	3723	3723
No. farmers	654	654	654	654
No. observations	27867	27863	27867	27863
Fixed effects	×	×	×	×
Controls for past heat		×		×

Notes: This table reports the effects of extreme heat on daily yield outcomes. Daily High-Quality Yield is defined as daily harvest in kg/acre in the highest-quality fruit grade. Daily Earnings per Acre is defined as the value of total daily harvest across all quality grades per acre. Fixed effects include farmer, week of crop lifecycle, calendar week, and day of week fixed effects. Past heat controls include a dummy for heat on the previous day exceeding 33°C as well as the number of days exceeding 33°C on days $t-2$ to $t-7$. Baseline mean refers to the mean outcome on days when maximum temperature does not exceed 33°C. Standard errors are clustered at the village level and reported in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

On days exceeding 33°C, farmers' yields are significantly reduced. High-quality yields fall by 9.6 kg per acre (column 1), representing a 16% decline relative to the mean on days where temperatures remain below 33°C. Daily earnings fall by INR 650 per acre (column 3), which is a decline of 17% compared to cooler days.

Importantly, these estimates are virtually unchanged when we control for past heat exposure. Comparing columns 1 and 2 in Panel A, the coefficient on hot days remains nearly identical: −9.62 kg without lagged heat controls versus −9.66 kg with controls for past heat. The same stability appears in Panel B and in the estimates for daily earnings. This insensitivity to lagged temperature controls confirms that the observed productivity losses reflect genuine same-day heat effects rather than lagged effects of prior heat stress. Since plant responses to heat stress unfold over time while human physiological responses occur within hours, these findings are consistent with productivity operating through human physiological responses to heat.

The intensity of heat exposure matters. Each additional hour above 33°C reduces high-quality yield by 2.0 kg per acre (Panel B, column 2) and harvest value by INR 131 per acre. This dose-response pattern is consistent with heat stress building over sustained exposure during the work day.

These effects are economically meaningful. Given the mean baseline yield of 60.4 kg per acre, and average daily earnings of INR 3,723 per acre on cooler days, heat-induced losses represent a 15% reduction in yield, and a 17% earnings loss (overall, including on lower quality fruit).

TABLE 3. Extensive and Intensive Margin Effects of Heat on Harvest Outcomes

	Extensive margin	Intensive margin (cond. on any harvest)	
	Any harvest	High-quality yield	Daily Earnings per Acre
	(1)	(2)	(3)
Panel A. Maximum temperature			
Max. temperature > 33°C	−0.055***	−8.250***	−600.9***
	(0.019)	(2.170)	(117.4)
Panel B. Duration of heat			
Each additional hour > 33°C	−0.008*	−2.208***	−150.3***
	(0.005)	(0.324)	(20.40)
Baseline mean	0.746	80.94	4989.5
No. farmers	654	654	654
No. observations	27,863	19,466	19,466
Fixed effects	×	×	×
Past heat controls	×	×	×

Notes: This table decomposes the effect of extreme heat into extensive and intensive margin responses. Column 1 examines the extensive margin: the dependent variable equals one if any harvest occurred on a scheduled pickup day, and zero otherwise. Columns 2 and 3 examine the intensive margin, restricting the sample to farmer-days when harvest actually occurred. Daily High-Quality Yield is defined as daily harvest in kg/acre in the highest-quality fruit grade. Daily Earnings per Acre is defined as the value of total daily harvest across all quality grades per acre. All specifications include farmer, week of crop lifecycle, calendar week, and day of week fixed effects, as well as controls for heat on the previous day exceeding 33°C and the number of days exceeding 33°C on days $t-2$ to $t-7$. Baseline mean refers to the mean outcome on days when maximum temperature does not exceed 33°C. Standard errors are clustered at the village level and reported in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Having established that same-day heat reduces daily yields, we now investigate the labor supply channels through which this occurs. Table 3 decomposes the overall same-day heat effect into two distinct margins of adjustment: whether farmers harvest at all on a given day (the extensive margin), and how much they harvest conditional on harvesting (the intensive margin).

Column (1) examines whether heat affects the probability of harvest occurring on a scheduled pickup day. The dependent variable equals one if any harvest is recorded, and zero otherwise. The results reveal substantial heat-induced absenteeism. When maximum temperature exceeds 33°C, the probability of harvest falls by 5.5 percentage points. Relative to the baseline harvest probability of 74.6%, this represents a 7.4% reduction in the likelihood that farmers harvest on hot days.

The hours-based specification reinforces this finding: each additional hour above 33°C reduces the probability of harvest by 0.8 percentage points. This pattern is consistent with farmers or workers opting out of harvesting when conditions become uncomfortably hot. Since the piece-rate contract does not mandate specific labor input and farmers can potentially defer harvest to adjacent days, skipping a hot day is a viable short-run adaptation strategy.

This extensive margin response has direct implications for farmer earnings. When no harvest occurs, daily income is zero. Given that hot days reduce harvest probability by 5.5 percentage points, a non-trivial share of the overall productivity loss operates through complete work stoppage rather than reduced effort.

Columns (2) and (3) restrict the sample to farmer-days when harvest actually occurred, examining high-quality yield and earnings per acre conditional on the farmer having harvested at all on that day. Even when farmers do harvest on hot days, yields are substantially lower. High-quality yield falls by 8.3 kg per acre when maximum temperature exceeds 33°C (column 2), and earnings decline by INR 601 per acre (column 3). Relative to the conditional means of 80.9 kg per acre and INR 4,990 per acre, respectively, this represents 10% reductions in both physical output and income.

Together, the results from Tables 2 and 3 suggest that the effect of heat on productivity operates through both margins: farmers are less likely to harvest at all when it is hot (extensive margin), and when they do harvest, they produce less (intensive margin). Just over one-third of the reduction in overall productivity comes from the extensive margin, and two-thirds from the intensive margin.[11] The fact that both margins respond to heat suggests that the effort costs are meaningful enough to alter labor supply decisions, but also that some harvesting constraints, such as the need to prevent fruit from growing too large, limit the ability to fully avoid hot days.

These dual margins of adjustment reveal both the flexibility and constraints facing smallholder farmers. The extensive margin response, simply not harvesting on the hottest days, is a form of behavioral adaptation that limits heat exposure. However, this comes at the cost of foregone earnings and potentially larger, lower-quality fruit on subsequent days. The persistent intensive margin effect shows that even when farmers choose to harvest, productivity suffers, consistent with heat stress impairing worker efficiency through fatigue, reduced work pace, or the need for more frequent breaks.

The combination of these effects underscores that heat imposes productivity costs that cannot be fully avoided through work timing alone. Even on days when farmers actively choose to harvest despite high temperatures, presumably because the costs of delaying are high, they still experience significant yield losses.

The results thus far establish that same-day heat significantly reduces yields, and that both the extensive and the intensive margin are at play. We now investigate whether farmers respond to anticipated or recent heat by shifting harvest timing across adjacent days. If workers know a hot day is coming, they might harvest more heavily the day before. Conversely, if they skip or reduce harvesting on a hot day, they might compensate by harvesting more intensively on the following day to catch up on fruit that has continued to ripen.

Such intertemporal substitution would reduce yield and income losses due to heat, even if only partial. If farmers can compensate for hot-day losses by harvesting more on adjacent cooler days, the actual

[11] From Tables 2 and 3, $-0.055 * 60.38/9.565 \approx 35\%$ and $8.250 * 0.746/9.656 \approx 65\%$.

productivity losses would be less severe than the same-day estimates suggest. Conversely, if we find no evidence of compensatory behavior, this would indicate that heat-induced productivity losses are not recoverable through retiming of effort, representing genuine reductions in total output and earnings.

Table 4 investigates these temporal dynamics by including controls for heat exposure on adjacent days. We examine whether yields respond to tomorrow's heat (forward-looking behavior) or yesterday's heat (delayed responses or catch-up), while maintaining our controls for cumulative heat over the previous week (days $t-2$ through $t-7$) to isolate these specific adjacent-day effects.

TABLE 4. Delayed and Forward-Looking Effects of Heat on Daily Yields and Earnings

	Daily High-Quality Yield			Daily Earnings/acre		
	(1)	(2)	(3)	(4)	(5)	(6)
Tomorrow's heat (>33°C)			1.540			21.99
			(1.943)			(111.9)
Today's heat (>33°C)	−9.618***	−9.656***	−10.25***	−661.5***	−646.8***	−655.2***
	(1.618)	(1.531)	(1.628)	(87.09)	(83.33)	(92.53)
Yesterday's heat (>33°C)		−1.304	−1.245		−152.8	−151.9
		(1.793)	(1.771)		(115.1)	(114.6)
No. heat days (>33°C) in past week ($t-2$ to $t-7$)		−2.022**	−1.934**		−168.7***	−167.4***
		(0.848)	(0.896)		(48.29)	(51.05)
Observations	27,867	27,863	27,863	27,867	27,863	27,863
Fixed effects	×	×	×	×	×	×

Notes: This table examines whether farmers engage in intertemporal substitution of labor by shifting harvest timing in response to heat on adjacent days. Daily High-Quality Yield is defined as daily harvest in kg/acre in the highest-quality fruit grade. Daily Earnings per Acre is defined as the value of total daily harvest across all quality grades per acre. Column 1 and 4 show the baseline specification with only today's heat. Column 2 and 5 add controls for yesterday's heat (day $t-1$) and cumulative past heat (days $t-2$ to $t-7$). Column 3 and 6 additionally include tomorrow's heat (day $t+1$) to test for anticipatory responses. All specifications include farmer, week of crop lifecycle, calendar week, and day of week fixed effects. Standard errors are clustered at the village level and reported in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

The table progressively adds temporal controls. Column (1) reproduces our baseline specification from table 2, showing the same-day heat effect without any controls for past or future heat. Column (2) adds yesterday's heat to test for delayed responses as well as the number of heat days in the past week. Column (3) adds a control for tomorrow's heat. Columns (4)-(6) repeat this progression using daily earnings per acre as the outcome.

The full specification in columns (3) and (6) reveals no evidence that farmers shift harvest timing in response to heat on adjacent days. Today's heat continues to have a large negative effect: when maximum temperature exceeds 33°C, high-quality yield falls by 10.3 kg per acre and earnings decline by INR 655 per acre. These estimates are almost identical to our baseline results in Table

2, confirming that the same-day effect is robust to controlling for heat exposure across multiple time periods.

Tomorrow's heat has no effect on today's harvest. The coefficient is small and statistically insignificant (1.54 kg for yields, INR 22 for earnings). If farmers anticipated hot weather and harvested more today to avoid working tomorrow, we would expect a positive and significant coefficient. The null result suggests that farmers do not or cannot systematically adjust today's harvest in response to expected heat tomorrow. This could reflect limited weather forecasting information, the physical difficulty of harvesting more than planned on a given day, or simply that the costs of deviating from the optimal harvest schedule outweigh the benefits of heat avoidance.

Yesterday's heat shows no positive effect, indicating an absence of catch-up behavior. The coefficient is actually slightly negative and statistically insignificant (−1.24 kg, -INR 152). If farmers reduced or skipped harvesting on hot days but then compensated by harvesting more intensively the following day, by collecting fruit that continued to ripen, we would expect a positive coefficient. Instead, we find no evidence of such compensatory behavior. When farmers reduce harvesting due to heat, they do not appear to make up for it the next day. This suggests the yield losses on hot days represent genuine productivity losses rather than merely redistributed harvest timing. The negative point estimate, while not statistically significant, may also hint at persistent fatigue: workers who were exposed to heat yesterday may still experience reduced capacity today, even if today's temperature is moderate.

Importantly, while yesterday's heat has no significant effect, cumulative heat over the past week does. Each additional day above 33°C during days $t-2$ through $t-7$ reduces today's yields by 1.93 kg and earnings by INR 167. This cumulative effect likely operates primarily through plant stress accumulation, with heat exposure during earlier developmental stages affecting current productivity, though persistent worker fatigue across multiple hot days could also contribute. While the losses due to cumulative past heat are substantial, the results support that the effects of past cumulative heat and same-day heat operate almost independently. Controlling for cumulative heat, the same-day effect remains large and stable at 10.3 kg, almost unchanged from our baseline estimates. This persistence across specifications reinforces our interpretation that the same-day effect, which arguably operates through human physiological responses to heat stress, is substantial and distinct from the plant-mediated cumulative effects.

The key takeaway from Table 4 is that heat-induced productivity losses do not appear to be shifted across time. Farmers neither anticipate and pre-empt hot days nor catch up afterward. Combined with our earlier findings that both extensive and intensive margins respond to heat, this temporal pattern suggests that the yield losses we observe represent genuine productivity costs rather than merely redistributed harvest timing. This has important implications for understanding farmer adaptation and welfare.

We now examine which farmers are most severely affected by heat, exploring whether heat sensitivity varies across different farmer characteristics. Table 5 presents results where we interact the heat indicator (maximum temperature exceeding 33°C) with farmer gender (Panel A), prior experience growing cucumbers (Panel B), age (Panel C), and self-reported difficulty hiring labor during harvest (Panel D). Each panel presents estimates for high-quality yields (column 1) and earnings per acre (column 2), with all specifications including our full set of controls from Table 2.

TABLE 5. Heterogeneous Effects of Extreme Heat on Daily Yield Outcomes

	Daily High-Quality Yield	Daily Earnings per Acre
	(1)	(2)
Panel A. Gender		
Heat	−9.630***	−635.7***
	(1.715)	(101.6)
Heat × Female	−0.059	−25.35
	(2.229)	(125.2)
Panel B. Farmer's Experience		
Heat	−10.73***	−713.6***
	(1.805)	(111.4)
Heat × Less experience	2.482	154.6
	(3.758)	(224.3)
Panel C. Age		
Heat	−7.683***	−515.8***
	(2.119)	(115.2)
Heat × Older age	−3.955	−262.5*
	(2.640)	(154.1)
Panel D. Labor Scarcity		
Heat	−4.691	−344.1*
	(3.226)	(203.4)
Heat × Hiring difficulties	−7.540*	−458.0*
	(4.180)	(251.7)
Fixed effects	×	×
Past heat controls	×	×

Notes: This table examines heterogeneous effects of extreme heat across farmer characteristics. Daily High-Quality Yield is defined as daily harvest in kg/acre in the highest-quality fruit grade. Daily Earnings per Acre is defined as the value of total daily harvest across all quality grades per acre. Each panel reports results from a separate regression interacting the heat indicator (daily maximum temperature exceeding 33°C) with a farmer characteristic. All specifications include farmer, week of crop lifecycle, calendar week, and day of week fixed effects, as well as controls for heat on the previous day exceeding 33°C and the number of days exceeding 33°C on days $t-2$ to $t-7$. The main effect captures the heat effect for the reference group. The interaction term captures the differential effect for the characteristic group. Standard errors are clustered at the village level and reported in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

If farmers could costlessly shift harvesting to cooler days, heat penalties would be limited to smaller inefficiencies in fruit size distribution. The absence of such substitution indicates that heat imposes binding constraints on labor supply that cannot be overcome through simple retiming of effort. The

piece-rate structure creates strong incentives to harvest at optimal times, yet heat exposure disrupts this schedule in ways that reduce both daily and cumulative earnings.

Panel A examines whether female farmers, who typically lead harvesting activities, experience different heat effects than male farmers. The main effect of heat is -9.63 kg for high-quality yield and -INR 636 for earnings, consistent with our baseline estimates. The interaction term is small and statistically insignificant (-0.06 kg, -INR 25), indicating that heat affects male and female farmers similarly. This suggests that the physiological heat stress experienced during harvest does not differ systematically by gender in this context, or that any gender differences in heat tolerance are offset by differences in adaptation strategies or labor allocation.

Panel B tests whether more experienced farmers are better able to cope with heat, perhaps through superior knowledge of optimal harvest timing or more effective labor management. We define less experienced farmers as those in the bottom half of the experience distribution (fewer than 3 seasons). The main effect shows that heat reduces yields by 10.7 kg and earnings by INR 714. The interaction term is positive but insignificant (2.48 kg, INR 155), providing no clear evidence that experience mitigates heat sensitivity. Both new and seasoned farmers appear equally vulnerable to same-day heat exposure.

Panel C explores whether older farmers (above median age of 40) are more sensitive to heat. The main effect for younger farmers is -7.68 kg for yields and -INR 516 for earnings. The interaction term is negative and larger in magnitude (-3.96 kg, -INR 263), with the earnings interaction reaching marginal significance ($p < 0.10$). This suggests that older farmers may experience somewhat larger productivity losses on hot days, consistent with age-related declines in heat tolerance documented in the occupational health literature. However, the differential effect is modest and not consistently significant across both outcomes.

Panel D provides the most striking heterogeneity result. We interact heat with an indicator for whether the farmer reported difficulty hiring labor during harvest, which 65% of farmers in our sample reported to face. The main effect of heat alone becomes statistically insignificant (-4.69 kg for yields, -INR 344 for earnings), while the interaction term is negative, substantial, and marginally significant (-7.54 kg, $p < 0.10$ for yields; -INR 458, $p < 0.10$ for earnings).

This pattern indicates that heat effects are concentrated among farmers who face binding labor constraints. For farmers without hiring difficulties, heat has minimal impact on yields. But for farmers who struggle to secure adequate labor, heat reduces yields by approximately 12 kg per acre (sum of main effect and interaction) and earnings by roughly INR 800 per acre.

This finding is strongly consistent with labor supply being the primary channel through which heat affects productivity. Cucumber harvesting is extremely labor intensive, requiring approximately five full-time workers per half-acre plot during peak harvest. When heat makes work unpleasant or physically demanding, farmers who can easily hire additional workers or reallocate family labor may be able to maintain productivity. But farmers facing labor scarcity, meaning those who are already operating at the margin of available labor, have no buffer to absorb heat-induced reductions in worker effort or availability. For these farmers, heat directly translates into lower output.

The fact that the unconditional heat effect (from earlier tables) seems to be driven almost entirely by the subset of farmers facing labor constraints provides further compelling evidence that same-day productivity losses operate primarily through the labor channel rather than through direct effects of

heat on plant biology. If heat were affecting yields primarily through plant stress, we would not expect labor market conditions to moderate the effect so strongly.

8. CONCLUSION

This paper provides novel micro-evidence on how same-day heat exposure affects productivity and labor supply in smallholder agriculture. Using high-frequency administrative data from hundreds of contract farmers growing cucumbers in South India, matched to hourly weather records, we document substantial productivity losses when daily temperatures exceed 33°C. On such days, farmers experience a 16% reduction in both yields and earnings compared to cooler days. These losses operate through both reduced likelihood of harvesting at all (extensive margin) and lower output conditional on harvesting (intensive margin).

Several features of our empirical design allow us to credibly isolate same-day heat effects from other potential confounds. Farm fixed effects account for time-invariant differences across farmers. Separate controls for crop-week and calendar-week account for the mechanical relationship between rising seasonal temperatures and the inverse-U shaped harvest pattern over the crop lifecycle. Controls for past heat exposure try to isolate genuine same-day effects rather than cumulative or lagged heat stress. The robustness of our estimates across these specifications strengthens confidence in the causal interpretation.

The pattern of results is consistent with heat operating primarily through labor rather than plant channels. First, the drop-off pattern we observe, relatively flat yields until 33°C, and a decline thereafter, mirrors physiological thresholds for human heat stress documented in experimental studies, while falling well within the optimal temperature range for the heat-tolerant cucumber varieties grown by these farmers. Second, same-day heat effects remain large and significant even after controlling for past heat exposure, which should capture cumulative plant stress from earlier developmental stages. Third, heterogeneity analysis reveals that heat effects are concentrated among farmers facing labor constraints, with a much smaller effect among farmers who report no difficulty hiring workers. This differential response would be difficult to reconcile with a plant-based mechanism but fits naturally with a labor-based explanation.

We find limited evidence that farmers can mitigate heat impacts through intertemporal substitution of labor. Neither anticipatory harvesting before hot days nor catch-up harvesting afterward appears to offset the productivity losses we document. This absence of temporal shifting suggests that the costs we measure represent genuine reductions in output rather than merely redistributed harvest timing. Combined with the piece-rate contract structure that creates strong incentives to harvest at optimal frequencies, this finding indicates that heat imposes binding constraints on labor supply that cannot be overcome through simple retiming of effort.

The same-day heat penalty is substantial. At current piece rates, a single heat day costs the average farmer roughly INR 650 per acre in lost earnings, representing 17% of crop total earnings. For smallholder farmers already operating near subsistence, such earnings losses can have serious consequences for household income, food security, and investment in future production.

Looking ahead, these findings have implications for climate adaptation policy. They highlight the need for heat-specific interventions beyond traditional agricultural extension which focus on inter-seasonal adaptation strategies such as crop selection and irrigation technology. Our results suggest

that intra-seasonal investments in labor productivity and worker health, whether through improved access to shade, hydration, or alternative work schedules, may also be impactful. Our results underscore the importance of social protection mechanisms that can smooth income in response to weather shocks, particularly in regions where heat stress is projected to intensify.

Several limitations suggest directions for future research. First, while our evidence strongly points to labor as the primary mechanism, we cannot directly observe labor inputs or worker-level effort. Studies combining farm-level outcomes with direct measures of time use, work intensity, or physiological strain would provide even more definitive evidence on behavioral pathways. Second, our study covers a single crop and region. Understanding how heat effects vary across crops with different labor intensities, across regions with different baseline climates, and across seasons with different adaptation opportunities would improve generalizability. Third, we observe farmers over a single season, limiting our ability to study longer-run adaptation through learning or capital investment. Panel studies following farmers over multiple years as they gain experience with heat exposure would shed light on the scope for adaptation over time.

Despite these limitations, our findings suggest that same-day heat may impose substantial productivity costs on smallholder farmers through its effects on labor supply and efficiency. As temperatures continue to rise, understanding and addressing these labor-mediated impacts will be crucial for protecting the livelihoods of the billions of people who depend on smallholder agriculture.

REFERENCES

Adhvaryu, Achyuta, Namrata Kala, and Anant Nyshadham, "The light and the heat: Productivity co-benefits of energy-saving technology," *Review of Economics and Statistics*, 2020, *102* (4), 779–792.

Agnolucci, Paolo, Chrysanthi Rapti, Peter Alexander, Vincenzo De Lipsis, Robert A Holland, Felix Eigenbrod, and Paul Ekins, "Impacts of rising temperatures and farm management practices on global yields of 18 crops," *Nature Food*, 2020, *1* (9), 562–571.

Amin, Bakht, Muhammad Jawaad Atif, Xiao Wang, Huanwen Meng, MI Ghani, M Ali, Y Ding, X Li, and Z Cheng, "Effect of low temperature and high humidity stress on physiology of cucumber at different leaf stages," *Plant Biology*, 2021, *23* (5), 785–796.

Aragón, Fernando M, Francisco Oteiza, and Juan Pablo Rud, "Climate change and agriculture: Subsistence farmers' response to extreme heat," *American Economic Journal: Economic Policy*, 2021, *13* (1), 1–35.

Borbon, Manuel Ivan Rodriguez, Hansuk Sohn, Efren Delgado, Donovan O Fuqua, Manuel Arnoldo Rodríguez Medina, Diego Tlapa, and Yolanda Baez-Lopez, "Shelf-life assessment on European cucumber based on accelerated temperature–humidity stresses," *Applied Sciences*, 2023, *13* (4), 2663.

Bröde, Peter, Dusan Fiala, Bruno Lemke, and Tord Kjellstrom, "Estimated work ability in warm outdoor environments depends on the chosen heat stress assessment metric," *International journal of biometeorology*, 2018, *62* (3), 331–345.

Burke, M., S. M. Hsiang, and E. Miguel, "Global non-linear effect of temperature on economic production," *Nature*, 2015, *527* (7577), 235–239.

Chen, Lin, Zhaojun Liang, Shuyan Xie, Wenrui Liu, Min Wang, Jinqiang Yan, Songguang Yang, Biao Jiang, Qingwu Peng, and Yu'e Lin, "Responses of differential metabolites and pathways to high temperature in cucumber anther," *Frontiers in Plant Science*, 2023, *14*, 1131735.

Cui, Xiaomeng and Qu Tang, "Extreme heat and rural household adaptation: Evidence from Northeast China," *Journal of Development Economics*, 2024, *167*, 103243.

Dasgupta, Shouro, Elizabeth JZ Robinson, Soheil Shayegh, Francesco Bosello, R Jisung Park, and Simon N Gosling, "Heat stress and the labour force," *Nature Reviews Earth & Environment*, 2024, *5* (12), 859–872.

_____, Nicole Van Maanen, Simon N Gosling, Franziska Piontek, Christian Otto, and Carl-Friedrich Schleussner, "Effects of climate change on combined labour productivity and supply: an empirical, multi-model study," *The Lancet Planetary Health*, 2021, *5* (7), e455–e465.

Dell, Melissa, Benjamin F. Jones, and Benjamin A. Olken, "Temperature Shocks and Economic Growth: Evidence from the Last Half Century," *American Economic Journal: Macroeconomics*, 2012, *4* (3), 66–95.

Dunne, John P, Ronald J Stouffer, and Jasmin G John, "Reductions in labour capacity from heat stress under climate warming," *Nature Climate Change*, 2013, *3* (6), 563–566.

El-Remaly, Eman, "Morphological, physio-biochemical, and molecular indications of heat stress tolerance in cucumber," *Scientific Reports*, 2023, *13* (1), 18729.

Fahad, Shah, Ali A Bajwa, Usman Nazir, Shakeel A Anjum, Ayesha Farooq, Ali Zohaib, Sehrish Sadia, Wajid Nasim, Steve Adkins, Shah Saud et al., "Crop production under drought and heat stress: plant responses and management options," *Frontiers in plant science*, 2017, *8*, 1147.

Flouris, Andreas D, Petros C Dinas, Leonidas G Ioannou, Lars Nybo, George Havenith, Glen P Kenny, and Tord Kjellstrom, "Workers' health and productivity under occupational heat strain:

a systematic review and meta-analysis," *The Lancet Planetary Health*, 2018, *2* (12), e521–e531.

González-Alonso, José, Christina Teller, Signe L Andersen, Frank B Jensen, Tino Hyldig, and Bodil Nielsen, "Influence of body temperature on the development of fatigue during prolonged exercise in the heat," *Journal of applied physiology*, 1999, *86* (3), 1032–1039.

Hancock, Peter A, Jennifer M Ross, and James L Szalma, "A meta-analysis of performance response under thermal stressors," *Human factors*, 2007, *49* (5), 851–877.

Heal, Geoffrey and Jisung Park, "Reflections—temperature stress and the direct impact of climate change: a review of an emerging literature," *Review of Environmental Economics and Policy*, 2016.

Hultgren, Andrew, Tamma Carleton, Michael Delgado, Diana R Gergel, Michael Greenstone, Trevor Houser, Solomon Hsiang, Amir Jina, Robert E Kopp, Steven B Malevich et al., "Impacts of climate change on global agriculture accounting for adaptation," *Nature*, 2025, *642* (8068), 644–652.

ILO, I, "Working on a warmer planet: the impact of heat stress on labour productivity and decent work," *Geneva: International Labour Organization*, 2019.

IPCC, "Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the IPCC," 2022. Available at https://www.ipcc.ch/report/ar6/wg2/.

Jagnani, Maulik, Christopher B Barrett, Yanyan Liu, and Liangzhi You, "Within-season producer response to warmer temperatures: Defensive investments by Kenyan farmers," *The Economic Journal*, 2021, *131* (633), 392–419.

Jayaraman, Rajshri, Debraj Ray, and Francis De Véricourt, "Anatomy of a contract change," *American Economic Review*, 2016, *106* (2), 316–358.

Jeffrey, Cara, Richard Trethowan, and Brent Kaiser, "Chickpea tolerance to temperature stress: Status and opportunity for improvement," *Journal of plant physiology*, 2021, *267*, 153555.

Kahn, Matthew E, Kamiar Mohaddes, Ryan NC Ng, M Hashem Pesaran, Mehdi Raissi, and Jui-Chung Yang, "Long-term macroeconomic effects of climate change: A cross-country analysis," *Energy Economics*, 2021, *104*, 105624.

Khayat, Moussa El, Dana A Halwani, Layal Hneiny, Ibrahim Alameddine, Mustapha A Haidar, and Rima R Habib, "Impacts of climate change and heat stress on farmworkers' health: A scoping review," *Frontiers in public health*, 2022, *10*, 782811.

Lai, Yun-Song, Di Shen, Wei Zhang, Xiaohui Zhang, Yang Qiu, Haiping Wang, Xinxin Dou, Sigeng Li, Yuanqi Wu, Jiangping Song et al., "Temperature and photoperiod changes affect cucumber sex expression by different epigenetic regulations," *BMC plant biology*, 2018, *18* (1), 268.

Lima, Cicero Z De, Jonathan R Buzan, Frances C Moore, Uris Lantz C Baldos, Matthew Huber, and Thomas W Hertel, "Heat stress on agricultural workers exacerbates crop impacts of climate change," *Environmental Research Letters*, 2021, *16* (4), 044020.

Lobell, D. B., W. Schlenker, and J. Costa-Roberts, "Climate trends and global crop production since 1980," *Science*, 2011, *333* (6042), 616–620.

LoPalo, Melissa, "Temperature, worker productivity, and adaptation: evidence from survey data production," *American Economic Journal: Applied Economics*, 2023, *15* (1), 192–229.

Lowder, Sarah K, Marco V Sánchez, and Raffaele Bertini, "Which farms feed the world and has farmland become more concentrated?," *World Development*, 2021, *142*, 105455.

Nath, Aditya, Subhashis Sahu, and Jason Kai Wei Lee, "An Umbrella Review of Systematic Reviews and Meta-Analyses on Occupational Heat Exposure, Health Risks, and Productivity Losses Globally," *Current Environmental Health Reports*, 2026, *13* (1), 2.

Ortiz-Bobea, Ariel, "The empirical analysis of climate change impacts and adaptation in agriculture," in "Handbook of agricultural economics," Vol. 5, Elsevier, 2021, pp. 3981–4073.

Parsons, Ken, "Occupational health impacts of climate change: current and future ISO standards for the assessment of heat stress," *Industrial health*, 2013, *51* (1), 86–100.

Phal, SONGHAK, THIDA Kem, VOUCHSIM Kong, BORARIN Buntong, and THONG Kong, "Assessment of the shelf-life of cucumber under three low-cost storage methods," *International Journal of Environmental and Rural Development*, 2013, *4* (2), 148–153.

Rana, M.K., P. Jansirani, L. Pugalendhi, and N. Meenakshi, "Gherkin," in M.K. Rana, ed., *Vegetable Crop Science*, CRC Press, 2017, pp. 437–446.

Rao, K Koteswara, TV Lakshmi Kumar, Ashwini Kulkarni, Chang-Hoi Ho, B Mahendranath, Srinivas Desamsetti, Savita Patwardhan, Appala Ramu Dandi, Humberto Barbosa, and Sudhir Sabade, "Projections of heat stress and associated work performance over India in response to global warming," *Scientific Reports*, 2020, *10* (1), 16675.

Rezaei, Ehsan Eyshi, Heidi Webber, Senthold Asseng, Kenneth Boote, Jean Louis Durand, Frank Ewert, Pierre Martre, and Dilys Sefakor MacCarthy, "Climate change impacts on crop yields," *nature reviews earth & environment*, 2023, *4* (12), 831–846.

Schlenker, Wolfram and Michael J Roberts, "Nonlinear temperature effects indicate severe damages to US crop yields under climate change," *Proceedings of the National Academy of sciences*, 2009, *106* (37), 15594–15598.

Shah, Arpit, Anish Sugathan, Deepak Malghan, Rockli Kim, and SV Subramanian, "Spatiotemporal changes in heat stress exposure in India, 1981-2023," *Nature Communications*, 2025, *16* (1), 9496.

Sheng, Di, Xin Zhao, James A Edmonds, Stephanie T Morris, Pralit Patel, Brian C O'Neill, Claudia Tebaldi, and Marshall A Wise, "Omitting labor responses underestimates the effects of future heat stress on agriculture," *Communications Earth & Environment*, 2025, *6* (1), 400.

Somanathan, Eswaran, Rohini Somanathan, Anant Sudarshan, and Meenu Tewari, "The impact of temperature on productivity and labor supply: Evidence from Indian manufacturing," *Journal of Political Economy*, 2021, *129* (6), 1797–1827.

Vecellio, Daniel J, Qinqin Kong, W Larry Kenney, and Matthew Huber, "Greatly enhanced risk to humans as a consequence of empirically determined lower moist heat stress tolerance," *Proceedings of the National Academy of Sciences*, 2023, *120* (42), e2305427120.

_____, S Tony Wolf, Rachel M Cottle, and W Larry Kenney, "Evaluating the 35 C wet-bulb temperature adaptability threshold for young, healthy subjects (PSU HEAT Project)," *Journal of Applied Physiology*, 2022, *132* (2), 340–345.

Wahid, Ashfaq Ahmad, Shabbir Gelani, Muhammad Ashraf, and Majid R. Foolad, "Heat tolerance in plants: An overview," *Environmental and Experimental Botany*, 2007, *61* (3), 199–223.

Wallace, John M and Peter V Hobbs, *Atmospheric science: an introductory survey*, Vol. 92, Elsevier, 2006.

Wang, Di, Peng Zhang, Shuai Chen, and Ning Zhang, "Adaptation to temperature extremes in Chinese agriculture, 1981 to 2010," *Journal of Development Economics*, 2024, *166*, 103196.

WHO and WMO, "Climate change and workplace heat stress: technical report and guidance of the World Health Organization and World Metereological Organization," `https://www.who.int/publications/i/item/9789240099814` 2025. Accessed: 2026-01-15.

Wolf, S Tony, Rachel M Cottle, Daniel J Vecellio, and W Larry Kenney, "Critical environmental limits for young, healthy adults (PSU HEAT Project)," *Journal of applied physiology*, 2022, *132*

(2), 327–333.

Yu, Bingwei, Fangyan Ming, Yonggui Liang, Yixi Wang, Yuwei Gan, Zhengkun Qiu, Shuangshuang Yan, and Bihao Cao, "Heat stress resistance mechanisms of two cucumber varieties from different regions," *International Journal of Molecular Sciences*, 2022, *23* (3), 1817.

Zhu, Peng, Jennifer Burney, Jinfeng Chang, Zhenong Jin, Nathaniel D Mueller, Qinchuan Xin, Jialu Xu, Le Yu, David Makowski, and Philippe Ciais, "Warming reduces global agricultural production by decreasing cropping frequency and yields," *Nature Climate Change*, 2022, *12* (11), 1016–1023.

Zivin, Joshua Graff and Matthew Neidell, "Temperature and the Allocation of Time: Implications for Climate Change," *Journal of Labor Economics*, 2014, *32* (1), 1–26.

APPENDIX A: ADDITIONAL FIGURES AND TABLES



(A) Soil preparation



(B) Sowing



(C) Plant maintenance



(D) Irrigation



(E) Pest management



(F) Harvesting

FIGURE A1. Cucumber cultivation *Notes.* This figure exemplifies the main activities involved in cucumber farming.



(A) Pickup truck



(B) Daily harvest



(C) Sorting



(D) High qual.



(E) Med. qual.

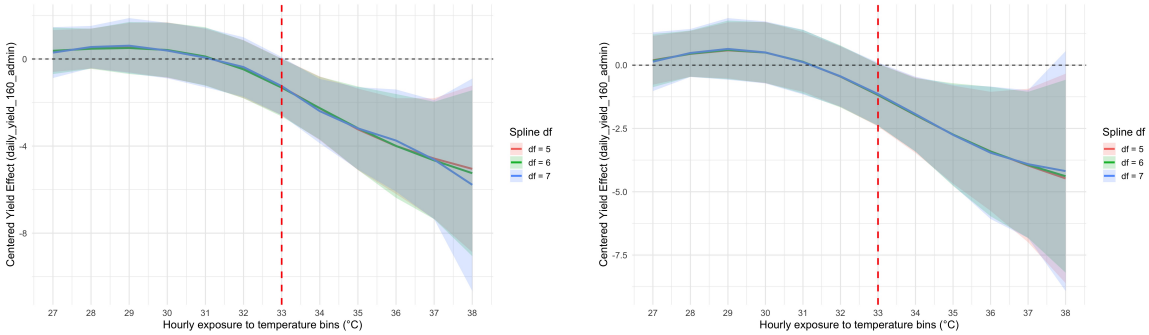


(F) Low qual.



(G) Sizes

FIGURE A2. Harvest *Notes.* This figure shows farm gate pickup and sorting of fruit into quality grades. The final pictures provides perspective for the four quality grades, from highest (smallest) to lowest (largest). Farmers are incentivized to harvest the highest viable quality grade.



(A) Without past heat controls

(B) With past heat controls

FIGURE A3. Threshold effects of same-day heat exposure on high-quality yield: degree-hours *Notes.* This figure depicts the relationship between same-day degree-hour exposure, and daily high-quality yields. Functions are estimated using a natural cubic spline

Appendix B: Proofs

Proof of Proposition 1. Fix (R_{it}, H_t) and consider an interior optimum $e^*_{it} > 0$ for

$$\max_{e_{it} \geq 0} \; pR_{it}\theta(e_{it}) - C(e_{it}; H_t) - F.$$

At an interior optimum the first-order condition is

$$pR_{it}\theta'(e^*_{it}) = C_e(e^*_{it}; H_t).$$

Differentiating with respect to H_t (noting that $e^*_{it} = e^*_{it}(H_t)$) yields

$$pR_{it}\theta''(e^*_{it})\frac{\partial e^*_{it}}{\partial H_t} = C_{ee}(e^*_{it}; H_t)\frac{\partial e^*_{it}}{\partial H_t} + C_{eH}(e^*_{it}; H_t).$$

Rearranging,

$$\frac{\partial e^*_{it}}{\partial H_t} = -\frac{C_{eH}(e^*_{it}; H_t)}{pR_{it}\theta''(e^*_{it}) - C_{ee}(e^*_{it}; H_t)}.$$

By the maintained second-order condition $pR_{it}\theta''(e^*_{it}) - C_{ee}(e^*_{it}; H_t) < 0$ and $C_{eH} > 0$, it follows that $\partial e^*_{it}/\partial H_t < 0$. Since $y_{it} = R_{it}\theta(e^*_{it})$ and $\theta'(e^*_{it}) > 0$,

$$\frac{\partial y_{it}}{\partial H_t} = R_{it}\theta'(e^*_{it})\frac{\partial e^*_{it}}{\partial H_t} < 0,$$

which proves Proposition 1.

Proof of Proposition 2. Define

$$V(R, H) = \max_{e \geq 0} \; pR\theta(e) - C(e; H) - F.$$

Since $C(0; H) = 0$ for all H and $C_{eH}(e; H) > 0$, it follows that for any $e > 0$,

$$C_H(e; H) = C_H(0; H) + \int_0^e C_{eH}(s; H)\, ds = \int_0^e C_{eH}(s; H)\, ds \geq 0,$$

so the objective is weakly decreasing in H for any fixed e. Under standard regularity conditions ensuring existence of a maximizer and differentiability of the value function in H, the envelope theorem implies

$$\frac{\partial V(R, H)}{\partial H} = -\, C_H(e^*(R, H); H) \leq 0.$$

Hence $V(R, H)$ is weakly decreasing in H. Because harvesting occurs if and only if $V(R_{it}, H_t) \geq 0$, higher same-day heat weakly reduces the probability that harvesting takes place, proving Proposition 2.