NBER WORKING PAPER SERIES

# THE IMPACT OF POLLUTION ON WORKER PRODUCTIVITY

Joshua S. Graff Zivin
Matthew J. Neidell

Working Paper 17004
http://www.nber.org/papers/w17004

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
April 2011

We thank numerous individuals and seminar participants at RAND, UC-Irvine, Maryland, Cornell, Tufts, Michigan, University of Washington, University of British Columbia, CUNY Graduate Center, Yale University, Columbia, UC-San Diego, and the NBER Health Economics meeting for helpful suggestions. We are also particularly indebted to Udi Sosnik for helping to make this project possible and Shlomo Pleban for assistance in collecting the data, both of Orange Enterprises. We are grateful for funding from the National Institute of Environmental Health Sciences (1R21ES019670-01), the Property and Environment Research Center, and seed grants from the Institute for Social and Economic Research and Policy and the Northern Manhattan NIEHS. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

The Impact of Pollution on Worker Productivity
Joshua S. Graff Zivin and Matthew J. Neidell
NBER Working Paper No. 17004
April 2011
JEL No. I1,J3,Q5

## ABSTRACT

Environmental protection is typically cast as a tax on the labor market and the economy in general. Since a large body of evidence links pollution with poor health, and health is an important part of human capital, efforts to reduce pollution could plausibly be viewed as an investment in human capital and thus a tool for promoting economic growth. While a handful of studies have documented the impacts of pollution on labor supply, this paper is the first to rigorously assess the less visible but likely more pervasive impacts on worker productivity. In particular, we exploit a novel panel dataset of daily farm worker output as recorded under piece rate contracts merged with data on environmental conditions to relate the plausibly exogenous daily variations in ozone with worker productivity. We find robust evidence that ozone levels well below federal air quality standards have a significant impact on productivity: a 10 ppb decrease in ozone concentrations increases worker productivity by 4.2 percent.

Joshua S. Graff Zivin
University of California, San Diego
9500 Gilman Drive, MC 0519
La Jolla, CA 92093-0519
and NBER
jgraffzivin@ucsd.edu

Matthew J. Neidell
Department of Health Policy and Management
Columbia University
600 W 168th Street, 6th Floor
New York, NY 10032
and NBER
mn2191@columbia.edu

## 1. Introduction

As one of the primary factors of production, labor is an essential element in every nation's economy. Investing in human capital is widely viewed as a key to sustaining increases in labor productivity and economic growth. While health is increasingly seen as an important part of human capital, environmental protection, which typically promotes health, has not been viewed through this lens. Indeed, such interventions are typically cast as a tax on producers and consumers, and thus a drag on the labor market and the economy in general. Given the large body of evidence that causally links pollution with poor health outcomes (e.g., Chay and Greenstone, 2003; Currie and Neidell, 2005; Dockery et al., 1993; Pope et al. 2002; Bell et al. 2004), it seems plausible that efforts to reduce pollution could in fact also be viewed as an investment in human capital and thus a tool for promoting, rather than retarding, economic growth.

The key to this assertion lies in the impacts of pollution on labor market outcomes. While a handful of studies have documented impacts of pollution on labor supply (Ostro, 1983; Hausman et al., 1984; Graff Zivin and Neidell, 2010; Carson et al., 2010; Hanna and Oliva, 2011)[2], their focus on the extensive margin, where behavioral responses are non-marginal, only captures high-visibility labor market impacts. Pollution is also likely to have productivity impacts on the intensive margin, even in cases where labor supply remains unaffected. Since worker productivity is more difficult to monitor than labor supply, these more subtle impacts may be pervasive throughout the workplace, so that even small individual effects may translate into large welfare losses when aggregated across the economy. There is, however, no systematic

[2] Numerous cost-of-illness studies that focus on hospital outcomes such as length of hospital stay also implicitly focus on labor supply impacts.

evidence to date on the direct impact of pollution on worker productivity.[3] This paper is the first to rigorously assess this environmental productivity effect.

Estimation of this relationship is complicated for two reasons. One, although datasets frequently measure output per worker, these measures do not isolate worker productivity from other inputs (i.e., capital and technology), so that obtaining clean measures of worker productivity is a perennial challenge. Two, exposure to pollution levels is typically endogenous. Since pollution is capitalized into housing prices (Chay and Greenstone, 2005), individuals may sort into areas with better air quality depending, in part, on their income, which is a function of their productivity (Banzhaf and Walsh, 2008). Furthermore, even if ambient pollution is exogenous, individuals may respond to ambient levels by reducing time spent outside, so that their exposure to pollution is endogenous (Neidell, 2009).

In this paper, we use a unique panel dataset on the productivity of agricultural workers to overcome these challenges in analyzing the impact of ozone pollution on productivity. Our data on daily worker productivity is derived from an electronic payroll system used by a large farm in the Central Valley of California who pays their employees through piece rate contracts. A growing body of evidence suggests that piece rates reduce shirking and increase productivity over hourly wages and relative incentive schemes, particularly in agricultural settings (Paarsch and Shearar, 1999, 2000; Lazear, 2000; Shi, 2010; Bandiera et al. 2005, 2010). Given the incentives under these contracts, our measures of productivity can be viewed as a reasonable proxy for productive capacity under typical work conditions.

We conduct our analysis at a daily level to exploit the plausibly exogenous daily fluctuations in ambient ozone concentrations. Although aggregate variation in environmental

[3]In a notable case study, Crocker and Horst (1981) examined the impacts of environmental conditions on 17 citrus harvesters. They found a small negative impact on productivity from rather substantial levels of pollution in Southern California in the early 1970s.

conditions is largely driven by economic activity, daily variation in ozone is likely to be exogenous. Ozone is not directly emitted but forms from complex interactions between nitrogen oxides (NOx) and volatile organic chemicals (VOCs), both of which are directly emitted, in the presence of heat and sunlight. Thus, ozone levels vary in part because of variations in temperature, but also because of the highly nonlinear relationship with NOx and VOCs. For example, the ratio of NOx to VOCs is almost as important as the level of each in affecting ozone levels (Auffhammer and Kellogg, 2011), so that small *decreases* in NOx can even lead to *increases* in ozone concentrations, which has become the leading explanation behind the "ozone weekend effect" (Blanchard and Tanenbaum, 2003). Moreover, regional transport of NOx from distant urban locations, such as Los Angeles and San Francisco, has a tremendous impact on ozone levels in the Central Valley (Sillman, 1999). Given the limited local sources of ozone precursors, this suggests that the ozone formation process coupled with emissions from distant urban activities are the driving forces behind the daily variation in environmental conditions observed near this farm.

Furthermore, the labor supply of agricultural workers is highly inelastic in the short run. Workers arrive at the field in crews and return as crews, thus spending the majority of their day outside regardless of environmental conditions. Moreover, since we have measures of both the decision to work and the number of hours worked, we can test whether workers respond to ozone, and in fact we are able to rule out even small changes in avoidance behavior. Thus, focusing on agricultural workers greatly limits the scope for avoidance behavior, further ensuring that exposure to pollution is exogenous in this setting, and that we are detecting productivity impacts on the intensive margin.

After merging this worker data with environmental conditions based on readings from air quality and meteorology stations in the California air monitoring network, we estimate econometric models that relate mean ozone concentrations during the typical work day to productivity. We find that ozone levels well below federal air quality standards have a significant impact on productivity: a 10 ppb decrease in ozone concentrations increases worker productivity by 4.2 percent. These effects are robust to various specification checks, such as flexible controls for temperature, inclusion of lagged ozone concentrations, and the inclusion of worker fixed effects.

Although these workers are paid through piece rate contracts, worker compensation is subject to minimum wage rules, which can alter the incentive for workers to supply costly effort. To account for potential concerns about shirking, we artificially induce "bottom-coding" on productivity measures for observations where the minimum wage binds, and estimate both parametric and semi-parametric censored regression models. Under this specification, the actual measures of productivity when the minimum wage binds no longer influence estimates of the impact of ozone on productivity. Thus, if the marginal effects of productivity on this latent variable differ from the marginal effects from our baseline linear model, this would indicate shirking is occurring. Our results, however, remain unchanged, suggesting that the threat of termination provides sufficient incentives for workers to supply effort even when compensation is not directly tied to output. Consistent with this explanation, we find that employee separations are significantly correlated with low-levels of productivity.

These impacts are particularly noteworthy, as the U.S. Environmental Protection Agency is currently contemplating a reduction in the federal ground-level ozone standard of approximately 10 ppb (EPA, 2010). The environmental productivity effect estimated in this paper offers a novel measure of morbidity impacts that are both more subtle and more pervasive than the standard health impact measures based on hospitalizations and physician visits. Moreover, they have the advantage of already being monetized for use in the regulatory cost-benefit calculations required by Executive Order 12866. In developing countries, where environmental regulations are typically less stringent and agriculture plays a more prominent role in the economy, this environmental productivity effect may have particularly detrimental impacts on national prosperity.

The paper is organized as follows. Section 2 describes the piece rate and environmental data. Section 3 provides a conceptual framework that largely serves to guide our econometric model, which is described in Section 4. Section 5 describes the results, with a conclusion provided in Section 6.

## 2. Data

Our data comes from a unique arrangement with an international software provider, Orange Enterprises (OE). OE customizes paperless payroll collection for clients, called the Payroll Employee Tracking (PET) Tiger software system. It tracks the progress of employees by collecting real-time data on attendance and harvest levels of individual farm workers in order to facilitate employee and payroll management. The PET Tiger software operates as follows. The software is installed on handheld computers used by field supervisors. At the beginning of the day, supervisors enter the date, starting time, and the crop being harvested. Each employee clocks in by scanning the unique barcode on his or her badge. Each time the employee brings a bushel, bucket, lug, or bin, his or her badge is swiped, recording the unit and time. Data collected in the field is transmitted to a host computer by synchronizing the handheld with the host computer, which facilitates the calculation of worker wages.

We have purchased the rights to data from a farm in the Central Valley of California that uses this system. To protect the identity of the farm, we can only reveal limited information about their operations. The farm, with a total size of roughly 500 acres, produces blueberries and two types of grapes during the warmer months of the year. The farm offers two distinct piece rate contracts depending on the crop being harvested: time plus pieces (TPP) for the grapes and time plus all pieces (TPAP) for blueberries. Total daily wages ($w$) from each contract can be described by the following equations:

(1) TPP: $w = 8h + p \cdot (q - minpcs \cdot h) \cdot I(q > minpcs \cdot h)$

TPAP: $w = 8h + p \cdot q \cdot I(q > minpcs \cdot h)$

where the minimum wage is \$8 per hour, $h$ is hours worked, $p$ is the piece rate, $q$ is daily output, *minpcs* is the minimum number of hourly pieces to reach the piece rate regime, and $I$ is an indicator function equal to 1 if the worker exceeds the minimum daily harvest threshold to qualify for piece rate wages and 0 otherwise. In both settings, if the worker's average hourly output does not exceed *minpcs*, the worker earns minimum wage. The marginal incentive for a worker whose output places them in the minimum wage portion of the compensation schedule is job security. In TPP, the marginal incentive in the piece rate regime is the piece rate. TPAP slightly differs from TPP in that it pays piece rate for *all* pieces when a worker exceeds the minimum hourly rate (as opposed to paying piece rate only for the pieces above the minimum). Hence, the payoff at *minpcs* is non-linear and thus provides a stronger incentive to reach this threshold under this contract. The incentive beyond this kink remains linear as under TPP.

The worker data set we obtained consists of a longitudinal file that follows workers over time by assigning workers a unique identifier based on the barcode of their employee badge. It includes information on the total number of pieces harvested by each worker[4], the location of the field, the type of crop, the terms of the piece rate contract[5], time in and out, and the gender of the worker.[6] Data quality is extremely high, as its primary purpose is to determine worker wages. The analyses in this paper are based on data from the farm for their 2009 and 2010 growing seasons.

Our measures of environmental conditions come from data on air quality and weather from the system of monitoring networks maintained by the California Air Resources Board. These data offer hourly measures of various pollutants and meteorological elements at numerous monitoring sites throughout the state. The farm is in close proximity to several monitors: three monitors that provide measurements of ozone and other environmental variables are within 20 miles of the farm, with the closest less than 10 miles away.[7] For all environmental variables, we compute an average hourly measure for the typical work day, 6 am – 3 pm.

We assign environmental conditions to the farm using data from the closest monitoring station to the farm. While studies find that ozone measurements at fixed monitors are often

[4] For the two types of grapes, harvests are done in crews of 3 and individual productivity is measured as the total output of the crew divided by the crew size. While crew work could introduce free-riding incentives, our measure of the environmental productivity effect will only be biased if these incentives change due to pollution. This will only occur if both of the following are true: workers are differentially affected by ozone and the complementarities in team production are very high (e.g., Leontief production). While each member of a crew has a specific task, they typically help each other throughout the day, suggesting that labor is indeed substitutable within the crew. Moreover, Hazucha et al. (2003) find little evidence of heterogeneous health impacts of ozone across healthy men and women. Thus, assigning average productivity measures to individuals within a crew should not bias our estimates.

[5] Piece rate contracts are fixed to the crop for the duration of the season. For simplicity, we label the two types of grapes as two crops given that they have different contracts.

[6] Although we have limited data on the demographic characteristics of our workers, demographics of piece-rate agricultural workers in California obtained from the National Agricultural Workers Survey, an employment-based random survey of agricultural workers, indicates these workers are poor, uneducated, and speak limited English, with the vast majority migrants from Mexico.

[7] To protect the identity of the farm we can not reveal the exact distance.

higher than measurement from personal monitors attached to individuals in urban settings (O'Neill et al., 2003), this is less of a concern in the agricultural setting where ratios of personal to fixed monitors have been found to be as high as 0.96 (Brauer and Brook, 1995). Furthermore, even when the difference exists, the within-person variation is highly correlated with the within-monitor variation (O'Neill et al., 2003). As a crude test for spatial uniformity of ozone levels, we regress ozone levels from the closest monitor to the farm against the second closest monitor, which is roughly 15 miles away, and obtain an R-squared of 0.88.[8] Thus, despite its simplicity, we expect measurement error using our proposed technique for assigning ozone to the farm to be quite small.

Our data follows roughly 1,600 workers intermittently over 155 days. Table 1 shows summary statistics for worker output, environmental variables, and a breakdown of the sample size. There are three main crops harvested by this farm.[9] Under the TPAP contracts (which are used to harvest crop type 1), workers are far less likely to reach the piece rate regime, with this happening for only 24% of workers compared to 57% and 47% for the other two crops, which are paid under TPP. Among those workers whose output exceeds the levels that correspond to the $8 per hour minimum wage, the average hourly wages are $8.20, $8.28, and $8.88 for each of the three crops, respectively. We also see that variation in worker output is equally driven by variation within as well as across workers.

In terms of environmental variables, the average ambient ozone level for the day is under 50 ppb, with a standard deviation of 13 ppb and a maximum of 86 ppb. Since this measure of ozone is taken over the average work day from 6 am – 3 pm, it corresponds closely with national

---

[8] Comparable R-squared for temperature is 0.94 and for particulate matter less than 2.5 μg/m$^3$, another pollutant of much interest, is only 0.27; hence we do not focus on this important pollutant.

[9] The timing of the harvest determines when each crop is ready to be picked, so workers can not choose the crop on any given day.

ambient air quality standards (NAAQS), which are based on 8-hour ozone measures. Current NAAQS are set at 75 ppb, suggesting that, while ozone levels during work hours can lead to exceedances of air quality standards, most work days are not in violation of regulatory standards.[10] Consistent with the area being prone to ozone formation, mean temperature and sunlight (as proxied by solar radiation) are high and precipitation is low.

For a deeper look at productivity, Figure 1 plots the distribution of average pieces collected per hour by crop and overall, with a line drawn at the rate that corresponds with the level of productivity that separates the minimum wage from the piece rate regime (the regime threshold). To combine productivity across crops, we standardize average hourly productivity by subtracting the minimum number of pieces per hour required to reach the piece rate regime and dividing by the standard deviation of productivity for each crop, so the value that separates regimes is 0. We can inspect these distributions to assess prima facie evidence of shirking. If shirking occurs when the minimum wage binds, then we would expect part of the distribution to be shifted away from the area just left of the regime threshold and into the left tail. These plots, however, do not exhibit such patterns. For the two crops paid TPP, the distribution of productivity follows a symmetric normal distribution quite closely. For the crop paid TPAP, we do see evidence of mass displaced just before the regime threshold. However, this mass is not moved to the left tail but is instead shifted towards the right of the threshold. Consistent with the strong incentives associated with just crossing the threshold under this payment scheme, workers who are just below the threshold appear to increase their effort. The pattern in all figures is consistent with the notion that shirking among those receiving a fixed wage is minimal, while sorting around the regime threshold for crop 1 is not trivial.

[10] Violation of NAAQS is based on the daily maximum 8-hour ozone. Since our measure of ozone begins at 6am, a time when ozone levels are quite low, the daily maximum 8-hour ozone is likely to be higher than our measure.

The significant variation in pieces collected in Figure 1 is also noteworthy, as this is critical for obtaining precise estimates of the impact of ozone. Figures 2 and 3 further illustrate this variation both within and across workers. For Figure 2, we collapse the data to the worker level by computing each worker's mean daily productivity over time. For Figure 3, we collapse the data to the daily level by computing the mean output of all workers on each day. This significant variation suggests that both worker ability and environmental conditions appear to be important drivers of worker productivity.

To illustrate the relationship between ozone and temperature, Figure 4 plots the demeaned average hourly ozone and temperature by day for the 2010 ozone season, with an indicator for days on which harvesting occurs. This Figure reveals considerable variation in both variables over time. Importantly, while ozone and temperature are often correlated – temperature is an input into the production of ozone – there is ample independent variation for conducting our proposed empirical tests.[11] We also take several steps to control for temperature flexibly to ensure that we are properly accounting for this relationship.

## 3. Conceptual framework

In this section, we develop a simple conceptual model to illustrate worker incentives under a piece rate regime with a minimum wage guarantee. We begin by assuming that the output $q$ for any given worker is a function of effort $e$ and pollution levels $\Omega$. Workers are paid piece rate $p$ per unit output, but only if their total daily wage is at least as large as the daily minimum wage $\bar{y}$.[12] In anticipation of our empirical model, we let zero denote the threshold

[11] The R-squared from a regression of ozone on temperature alone is 0.61. When we more flexibly control for temperature and also include additional environmental variables, the R-squared increases to 0.70.
[12] While minimum wage standards are typically fixed at an hourly rate, the fixed length workday in our setting allows us to translate this into a daily rate.

level of output at which workers graduate from the minimum wage regime. Since employment contracts are extremely short-lived, we assume that the probability of job retention $\tau$ is an increasing function of output levels $q$ when $q<0$.[13] Denoting the costs of worker effort as $c(e)$ and the value associated with job retention as $k$, we can characterize the workers' maximization problem above and below the threshold output level.

For those workers whose output level qualifies them for the piece rate wage ($q \geq 0$), effort will be chosen in order to maximize the following:

(2) $\text{Max}_e \; p \cdot q(e, \Omega) - c(e)$.

For those workers whose output level places them under the minimum wage regime ($q<0$), effort will be chosen to maximize the following:

(3) $\text{Max}_e \; \overline{y} - \tau(q(e,\Omega))k - c(e)$.

The first order conditions for each are:

(2') $p \cdot \frac{\partial q}{\partial e} - \frac{\partial c}{\partial e} = 0$;

(3') $-\frac{\partial \tau}{\partial q}\frac{\partial q}{\partial e}k - \frac{\partial c}{\partial e} = 0$.

Under the piece rate regime, workers will supply effort such that the marginal cost of that effort is equal to additional compensation associated with that effort. For those workers being paid minimum wage, the incentive to supply effort is driven entirely by concerns about job security.[14] Workers supply effort such that the marginal cost of that effort is equal to the increased probability of job retention associated with that effort times the value of job retention.

---

[13] The assumption of perfect retention for those above the threshold is made for simplicity. As long as the probability of job retention is higher for those workers whose harvest levels exceed the threshold, the basic intuition behind the results that follow remain unchanged.

[14] This is conceptually quite similar to the model of efficiency wages and unemployment advanced in Shapiro and Stiglitz (1984), where high wages and the threat of unemployment induce workers to supply costly effort.

The threat of punishment for low levels of output is instrumental in inducing effort under the minimum wage regime. If workers are homogenous and firms set contracts optimally, the gains from job retention due to extra effort will be set equal to the piece rate wage, i.e. $-\frac{\partial \tau}{\partial q}k = p$, such that effort exertion will be identical across both segments of the wage contract. If firms are unable to design optimal contracts, effort will differ across regimes. Of particular concern is the situation in which termination incentives are low-powered, i.e. $-\frac{\partial \tau}{\partial q}k < p$. In this case, workers essentially have a limited liability contract and thus have incentives to shirk under the minimum wage regime. Moreover, since the productivity impacts of pollution increase the probability of workers falling under the minimum wage portion of the compensation scheme, pollution will also indirectly increase the incentive to shirk. Accounting for these potentially different responses to pollution across regimes is central to our econometric model.

## 4. Econometric Model

The worker maximization problem characterized in the previous section suggests the following econometric model:

(4) $E[q|\Omega,X] = P(q\geq 0|\Omega,X)*E[q|\Omega,X,q\geq 0] + (1-P(q\geq 0|\Omega,X))*E[q|\Omega,X,q<0]$

where *P* is the probability a worker has output high enough to place them in the piece rate regime, *1-P* is the probability a worker's output places them in the minimum wage regime, and *X* are other factors that affect productivity (described in more detail below). We are primarily interested in the direct effect of pollution on productivity (the environmental productivity effect). Since there is no incentive to shirk in the piece rate regime, $\delta q/\delta\Omega$ represents the environmental productivity effect.[15] To the extent that there is an incentive to shirk in the minimum wage regime, $\delta q/\delta\Omega$ will reflect not only the environmental productivity effect but also the indirect effect due to the interaction of this pollution effect with shirking incentives.

We use two approaches for estimating this equation. First, we estimate a linear model using all worker-day observations regardless of output levels and thus the payment regime obtained that day:

(5) $$q = \beta^{ols}\Omega + \theta^{ols}X + \varepsilon^{ols}$$

where $\beta^{ols}$ is the sum of the direct impact and, if it exists, the indirect impact of pollution on productivity. If the piece rate contract is set optimally by imposing an appropriate termination threat as described in the previous section, there is no incentive to shirk, and $\beta^{ols}$ will only capture the environmental productivity effect. To the extent that contracts are not set optimally and there is an incentive to shirk in the minimum wage regime, $\beta^{ols}$ will instead provide an upper bound of the estimate of the environmental productivity effect because it will also include the indirect effect of pollution on productivity via shirking.

As a second approach, we estimate equation (4) by artificially "bottom-coding" our data and estimating censored regression models. To do this, we leave all observations in the piece rate regime as is, but assign a measure of productivity of 0 to all observations in the minimum wage regime.[16] Thus, our estimation strategy can be viewed as a Type I Tobit model of the following form:

(6) $$q^* = \beta^{cen}\Omega + \theta^{cen}X + \varepsilon^{cen}$$

$$q = q^* \text{ if } q \geq 0$$

[15] Although environmental conditions may affect workers, they may also have a direct impact on crops. While there is considerable evidence to support that chronic exposure to ozone affects crop yield (e.g., see Manning, 2003), there is no evidence to support an effect from acute exposure.
[16] Because of our standardization of productivity, a value of 0 represents the value when workers switch from the minimum wage to piece rate regime.

$q = 0$ *if* $q<0$

where $q^*$ is the latent measure of productivity. Because we are interested in the impact of pollution on actual productivity, which can take on values less than zero, the environmental productivity effect is the marginal effect of pollution on the latent variable $q^*$, which is simply $\beta^{cen}$. Importantly, the actual values of productivity in the minimum wage regime will have no impact on the likelihood function, and hence on $\beta^{cen}$. That is, if shirking occurs so that the distribution of productivity in the minimum wage regime is shifted to the left, these observations will no longer influence estimates of $\beta^{cen}$ because they have been censored. Instead, only the observations in the piece rate regime will affect estimates of $\beta^{cen}$. Therefore, even if workers are shirking when paid minimum wage, our estimates of $\beta^{cen}$ will only capture the environmental productivity effect.

The estimates from these two models can, in turn, be compared to test for the existence of shirking. If workers shirk when the minimum wage binds, then we expect $\beta^{ols} > \beta^{cen}$. If workers do not shirk when the minimum wage binds, then we expect $\beta^{ols} = \beta^{cen}$.

We include data from all crops in one regression by using the standardized measures of productivity described in the data section, so the coefficients can be interpreted as a standard deviation change in productivity from a 1 ppb change in ozone. To control for other time-varying factors that may affect productivity, the vector $X$ includes a quadratic in temperature, humidity, precipitation, wind speed, air pressure, and solar radiation, all measured as the mean over the typical work-day. $X$ also includes a series of day-of-week indicators to capture possible changes in productivity throughout the week, indicator variables for the crop to account for the mean shift in productivity from different contracts, and year-month dummies to control for trends in pollution and productivity within and across growing seasons. All standard errors are two-way clustered on the date because the same environmental conditions are assigned to all workers on a given day and on the worker to account for serial correlation in worker productivity.

Two facts about how ozone affects health are relevant for the econometric model. One, chamber studies, which randomly expose a small number of healthy, young adults to varying levels of ozone, find that exposure to ozone can affect lung functioning in as quickly as within 1-2 hours, with effects exacerbated by exercise and with continued duration of exposure (see, e.g., Gong et al., 1986; Kulle et al., 1985; McDonnell et al., 1983). These findings have generally been confirmed in the field using outdoor workers: mail carriers in Taichung City, Taiwan and agricultural workers in Fraser Valley, Canada show decrements in lung functioning on days with higher ozone concentrations (Chan and Wu, 2005; Brauer et al., 1996). As such, we expect the impact of ozone on productivity to be contemporaneous, particularly given the strenuous nature of this work and duration of exposure. Two, recovery from ozone pollution is fairly rapid when removed from exposure. Nearly all lung functioning returns to baseline levels in healthy adults within 24 hours of exposure, with recovery taking longer for hyperresponsive adults with underlying health conditions (Folinsbee and Horvath, 1989; Folinsbee and Hazucha, 2000).[17] Since ozone levels fall considerably overnight as heat and sunlight decline, we expect lagged ozone to have minimal impacts on the productivity of our healthy worker population. Given these two features of the dose-response to ozone, we focus our analysis on the contemporaneous relationship between ozone and productivity. Nonetheless, we explore the impact of lagged ozone concentrations in order to confirm that our workers are indeed healthy.

[17] Although lung functioning recovers after exposure, long term damage to lung cells may still occur (Tepper et al., 1989).

## 5. Results

To test the hypothesis that labor supply is inelastic in the short-run, we begin by focusing on whether work schedules respond to changes in ozone levels. We estimate linear regression models for the decision to work and the number of hours worked (conditional on working), both with and without worker fixed effects. Shown in Table 2, the results in the first two columns, which focus on the decision to work, do not support evidence of a labor supply response to ozone.[18] The second two columns also reveal that the number of hours worked is not significantly related to ozone levels. Even at the lower 95% confidence interval, a 1 ppb increase in ozone is associated with a 0.03 drop in hours worked, which is a roughly 1.5 minute decrease in hours worked. The insensitivity of these results to including worker fixed effects strengthens our confidence in these findings. Thus, consistent with our contention that avoidance behavior is not an issue in this setting, farm workers do not appear to adjust their work schedules in response to ozone levels.

In Table 3, we present our main results. Column (1) presents results from our linear regression model. The estimated coefficient suggests that a 1 ppb increase in ozone leads to a statistically significant decrease in productivity of .012 of a standard deviation. Based on the distribution of ozone and productivity in our sample, this estimate implies that a 10 ppb decrease in ozone increases worker productivity by 4.2 percent. If wage contracts are set optimally, this is an unbiased estimate of the effect of ozone pollution. If contracts are not set optimally and workers shirk when the minimum wage binds, then this estimate will overstate the impact of ozone. In column (2) we show results from a Type I Tobit model, where we artificially censor

[18] Marginal effects from logit and probit models for the decision to work are virtually identical to the results from the linear probability model.

observations when the minimum wage binds, and find an identical .012 standard deviation effect from a 1 ppb change in ozone.

Since this Tobit model assumes normality and homoskedasticity, we assess the sensitivity of our results to these assumptions by estimating a censored median regression model, also displaying results from an uncensored median regression model as a reference point.[19] Shown in column (3), the median regression estimate is quite comparable to the linear regression estimate, which is not surprising given the distribution of productivity shown in Figure 1. The censored median regression results, shown in column (4), are also quite similar to the estimates from the parametric censored models, lending support to the parametric assumptions. The comparability of the four estimates in this Table suggests that shirking due to the minimum wage is relatively minimal in this setting. Thus, the basic linear regression specification appears to yield unbiased estimates of the pollution productivity effect.

Although the lack of shirking in the minimum wage regime may appear surprising, as discussed in the conceptual framework, this can arise if the gains from job retention associated with providing effort are sufficiently large. This is particularly important in our setting where output is easily verified and labor contracts are extremely short-lived. In order to examine the potential importance of these features, we provide descriptive evidence on the relationship between worker productivity and separations. We define a separation as the last day we observe a worker in the data. Similar to Lazear (2000), Table 4 shows the rate of separation by decile of daily productivity. Immediately evident is that less productive workers are more likely to experience separations: 6.5 percent of workers whose productivity falls in the bottom decile on any given day separate from the farm, while only 2.5 percent in the top decile separate (this difference is statistically significant). As the next column shows, highly productive workers

[19] We estimate a censored median model using the 3-step procedure developed by Chernozhukov and Hong (2002).

typically have more tenure, so some of these differences in separations could be driven by differences in tenure. In column (3), we show separations by productivity after adjusting for the impact of tenure on productivity and find quite similar results. Although we can not identify the reason for a separation, these results are consistent with the idea that the threat of termination for less productive workers is reasonably high in this setting.

In Table 5, we explore the sensitivity of both our linear and Tobit estimates to various additional assumptions. Column (1) repeats the baseline results. In column (2) we include worker fixed effects. Although this increases the explanatory power of our regressions considerably, the estimates for ozone are largely unchanged, consistent with the notion that workers are not selecting into employment on any given day based on ozone concentrations.

Since ozone is formed in part because of temperature and sunlight, it is essential that we properly control for these variables. While we already control for a quadratic in mean temperature and solar radiation, we explore the sensitivity of the ozone estimates by also including daily minimum and maximum temperature and solar radiation (column 3), and by controlling for all three temperature measures more flexibly by using a series of indicator variables for every 5 degrees Fahrenheit instead of a quadratic (column 4). Our estimates for ozone remain largely unaffected by these changes, suggesting that, although ozone and temperature are highly correlated, the quadratic in mean temperature in our main specification adequately controls for temperature.

Figure 1 provided some evidence that worker effort changes near the regime threshold, particularly for crop 1 where contracts are time plus all pieces. If higher ozone levels reduce productivity and hence make it more likely for workers to fall into the minimum wage regime, this offsetting increase in effort may bias our results down. In the remaining two columns of

Table 5, we address this by excluding observations that are close to the regime threshold, varying our definition of "close."[20] Consistent with expectations, our results are slightly larger as we exclude more observations, but these differences are minimal.

To address potential concerns about the cumulative effect of ozone exposure, we also present results that include 1 and 2-day lags of ozone. Since ozone levels may only reflect exposure on days when workers actually work, we limit our focus to days when workers have worked the previous day by excluding from our analysis the first one or two days of the workweek depending on how many lags we include in our specification. Table 6, column (1) repeats our baseline results from the linear regression model. Shown in column (2) are results without any lags but excluding Monday, which are slightly higher than the baseline results. Including 1 lag of ozone, shown in column (3), we find that the coefficient on contemporaneous ozone remains the same, and lagged ozone is negative but statistically insignificant. The results in column (4) show that excluding the first two work days continues to increase the contemporaneous coefficient on ozone. Including two lags of ozone, column (5) shows that the coefficient on contemporaneous ozone remains statistically significant and again unchanged, while both lags of ozone are statistically insignificant. Together, these estimates suggest that the predominant effect of ozone is from same day exposure, with an overnight respite from ozone sufficient for lung functioning to return to baseline levels. Moreover, this rapid recovery implies that the environmental productivity effects measured in this paper are predominantly impacting a healthy population.[21]

[20] We also estimated models that completely excluded observations under the time plus all pieces contract, and our estimates for ozone were -.010 for the linear model and -.013 for the Tobit model, which are largely the same as those found when those observations were included.

[21] Recall from Section 4 that chamber studies suggest a rapid recovery from ozone exposure for healthy individuals.

## 6. Conclusion

In this paper, we merge a unique dataset on individual-level daily harvest rates for agricultural workers with data on environmental conditions to assess the impact of ozone pollution on worker productivity. We find that a 10 ppb change in average ozone exposure results in a significant and robust 4.2 percent change in agricultural worker productivity. Despite the applicability of minimum wages and the incentive to shirk, we find little evidence of differential effects depending on whether or not the minimum wage binds. Importantly, this environmental productivity effect suggests that common characterizations of environmental protection as purely a tax on producers and consumers to be weighed against the consumption benefits associated with improved environmental quality may be misguided. Environmental protection can also be viewed as an investment in human capital, and its contribution to firm productivity and economic growth should be incorporated in the calculus of policy makers.

Our results also speak to the ongoing debates on ozone policy. Ozone pollution continues to be a pervasive environmental issue throughout much of the world. Debates over the optimal level of ozone have ensued for many years, and current efforts to strengthen these standards remain contentious. Defining regulatory thresholds depends, in part, on the benefits associated with avoided exposure, which has traditionally been estimated through a focus on high-visibility health effects such as hospitalizations. The labor productivity impacts measured in this paper help make these benefits calculations more complete. Our results indicate that ozone, even at levels below current air quality standards in most of the world, has significant negative impacts on worker productivity, suggesting that the strengthening of regulations on ozone pollution would yield additional benefits.

These impacts of ozone on agricultural workers are also important in their own right. A back-of-the envelope calculation that applies the environmental productivity effect estimated in the Central Valley of California to the whole of the U.S. suggests that a 10 ppb reduction in the ozone standard would translate into an annual cost savings of approximately $1.1 billion in labor expenditure.[22] In the developing world, where national incomes depend more heavily on agriculture, these productivity effects are likely to have a much larger impact on the economy. These impacts may be especially large in countries like India, China, and Mexico, where rapid industrial growth and automobile penetration contribute precursor chemicals that contribute to substantially higher levels of ozone pollution.

While the impacts of ozone on agricultural productivity are large, the generalizability of these findings to other pollutants and industries is unclear. Agricultural workers face considerably higher levels of exposure to pollution than individuals who work indoors. That said, roughly 11.8 percent of the U.S. labor force works in an industry with regular exposure to outdoor conditions, and this figure is much higher for middle- and lower-income countries (Graff Zivin and Neidell, 2010). Moreover, many forms of outdoor pollution diminish indoor air quality as well. For example, indoor penetration of fine particulate matter ranges from 38-94% for typical residential homes in the US (Abt et al., 2000). Examining the generalizability of the environmental productivity effect estimated in this paper to other pollutants and industries represents a fruitful area for future research.

[22] Total labor expenditure in U.S. agriculture was approximately $26.5B in 2007 (USDA, 2009).

**References**

Abt, Eileen, Helen H. Suh, Paul Catalano, and Petros Koutrakis (2000). "Relative Contribution of Outdoor and Indoor Particle Sources to Indoor Concentrations." *Environmental Science and Technology*, 34 (17), pp 3579–3587.

Auffhammer, Maximilian and Ryan Kellogg (2011). "Clearing the Air? The Effects of Gasoline Content Regulation on Air Quality." *American Economic Review*, forthcoming.

Bandiera, Oriana, Iwan Barankay, and Imran Rasul (2005). "Social Preferences and the Response to Incentives: Evidence from Personnel Data." *Quarterly Journal of Economics,* 120(3): 917-962.

Bandiera, Oriana, Iwan Barankay, and Imran Rasul (2010). "Social Incentives in the Workplace." *Review of Economic Studies*, 77(2): 417-458.

Banzhaf, H. Spencer, and Randall Walsh (2008). "Do People Vote with Their Feet? An Empirical Test of Tiebout." *American Economic Review*, 98(3): 843–63.

Bell, Michelle, Aidan McDermott, Scott Zeger, Jonathan Samet, Francesca Dominici (2004). "Ozone and Short-term Mortality in 95 US Urban Communities, 1987-2000." *Journal of the American Medical Association*, 292 (19).

Blanchard, Charles and Shelley Tanenbaum (2003). "Differences between Weekday and Weekend Air Pollutant Levels in Southern California." *Journal of the Air and Waste Management Association*, 53(7).

Brauer, M and JR Brook (1995). "Personal and Fixed-Site Ozone Measurements with a Passive Sampler." *Journal of the Air and Waste Management Association*, 45 (7): 529-537.

Brauer, M, J Blair and S Vedal (1996). "Effect of ambient ozone exposure on lung function in farm workers." *Am. J. Respir. Crit. Care Med.*, 154(4): 981-987.

Carson, Richard, Phoebe Koundouri, and Céline Nauges (2010). "Arsenic Mitigation in Bangladesh: A Household Labor Market Approach." *American Journal of Agricultural Economics*, 92.

Chan, Chang-Chuan and Tsung-Huan Wu (2005). "Effects of Ambient Ozone Exposure on Mail Carriers' Peak Expiratory Flow Rates." *Environmental Health Perspectives*, 113(6): 735-738.

Chay, Kenneth and Michael Greenstone (2003). "The Impact of Air Pollution on Infant Mortality: Evidence from Geographic Variation in Pollution Shocks Induced by a Recession." *Quarterly Journal of Economics*, 118(3): 1121-1167.

Chay, Kenneth and Michael Greenstone (2005). "Does Air Quality Matter? Evidence from the Housing Market." *Journal of Political Economy*, 113: 376–424

Chernozhukov, Victor and Han Hong (2002). "Three-step censored quantile regression and extramarital affairs." *Journal of the American Statistical Association*, 97(459), 872-882

Currie, Janet and Matthew Neidell (2005). "Air Pollution and Infant Health: What Can We Learn from California's Recent Experience?" *Quarterly Journal of Economics*, 120(3): 1003-1030.

Dockery, Douglas W., C. Arden Pope, Xiping Xu, John D. Spengler, James H. Ware, Martha E. Fay, Benjamin G. Ferris, and Frank E. Speizer (1993). "An association between air pollution and mortality in six U.S. cities." *The New England Journal of Medicine*, 329:1753-1759.

Environmental Protection Agency (2010). "National Ambient Air Quality Standards for Ozone (Proposed Rule)." Federal Register 75:11 (January 19, 2010) p. 2938-3052.

Folinsbee, L. J., Hazucha, M. J. (2000). "Time course of response to ozone exposure in healthy adult females." *Inhalation Toxicol.* 12: 151-167.

Folinsbee, L. J., Horvath, S. M. (1986). "Persistence of the acute effects of ozone exposure." *Aviat. Space Environ. Med.* 57: 1136-1143.

Gong, H., Jr., Bradley, P. W., Simmons, M. S., Tashkin, D. P. (1986). "Impaired exercise performance and pulmonary function in elite cyclists during low-level ozone exposure in a hot environment." *Am. Rev. Respir. Dis.* 134: 726-733.

Graff Zivin, Joshua and Matthew Neidell (2010). "Temperature and the allocation of time: Implications for climate change." NBER working paper 15717.

Hanna, Rema and Paulina Oliva (2011). "The Effect of Pollution on Labor Supply: Evidence from a Natural Experiment in Mexico City." Mimeo.

Hazucha, M. J., L.J. Folinsbee, and P.A. Bromberg (2003). "Distribution and reproducibility of spirometric response to ozone by gender and age." *J. Appl. Physiol.* 95: 1917-1925.

Hausman, Jerry, Bart Ostro, and David Wise (1984). "Air Pollution and Lost Work." NBER Working Paper No. 1263.

Kulle, T. J., Sauder, L. R., Hebel, J. R., Chatham, M. D. (1985). "Ozone response relationships in healthy nonsmokers." *Am. Rev. Respir. Dis.* 132: 36-41.

Lazear, Edward (2000). "Performance pay and productivity." *American Economic Review*, 90(5): 1346-1361.

Manning, W.J. (2003). “Assessing plant responses to ambient ozone: Growth of ozone-sensitive loblolly pine seedlings treated with ethylenediurea (EDU) and sodium erythorbate (NaE).” *Environ. Pollut.*, 126(1): 73-81.

McDonnell, W. F., Horstman, D. H., Hazucha, M. J., Seal, E., Jr., Haak, E. D., Salaam, S. A., House, D. E. (1983). “Pulmonary effects of ozone exposure during exercise: dose-response characteristics.” *J. Appl. Physiol.: Respir.: Environ. Exercise Physiol.* 54: 1345-1352.

Neidell, Matthew (2009). “Information, Avoidance Behavior, and Health: The Effect of Ozone on Asthma Hospitalizations.” *Journal of Human Resources*, 44(2).

O'Neill MS, Ramirez-Aguilar M, Meneses-Gonzalez F, Hernández-Avila M, Geyh AS, Sienra-Monge JJ, Romieu I. (2003). “Ozone exposure among Mexico City outdoor workers.” *J Air Waste Manag Assoc.*, 53(3): 339-46.

Ostro, Bart (1983). “The Effects of Air Pollution on Work Lost and Morbidity." *Journal of Environmental Economics and Management*, 10(4): 371-382.

Paarsch, Harry, J. and Bruce Shearer (1999). “The Response of Worker Effort to Piece Rates: Evidence from the British Columbia Tree-Planting Industry." *Journal of Human Resources*, 34: 643-667.

Paarsch, Harry, J. and Bruce Shearer (2000). “Piece Rates, Fixed Wages, and Incentive Effects: Statistical Evidence from Payroll Records." *International Economic Review*, 40: 59-92.

Pope CA III, Burnett RT, Thun MJ, Calle EE, Krewski D, Ito K, Thurston GD (2002). “Lung Cancer, Cardiopulmonary Mortality and Long-term Exposure to Fine Particulate Air Pollution.” *Journal of the American Medical Association,* 287:1132-1141.

Shapiro, Carl and Joseph Stiglitz (1984). “Equilibrium unemployment as a worker discipline device.” *American Economic Review*, 74(3).

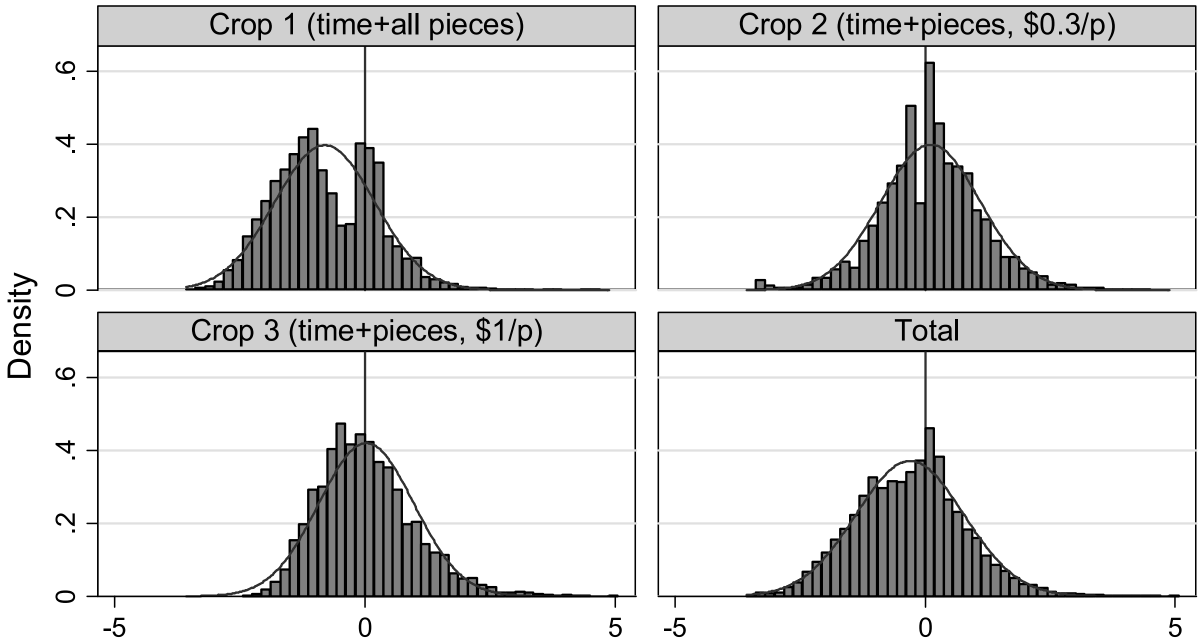
Shi, Lan (2010). “Incentive Effect of Piece Rate Contracts: Evidence from Two Small Field Experiments.” *The B.E. Journal of Economic Analysis & Policy*, 10(1) (Topics).

Sillman, Sanford (1999). “The Relation Between Ozone, NOx, and Hydrocarbons in Urban and Polluted Rural Environments.” *Atmospheric Environment*, 33: 1821-1845

Tepper, J. S., Costa, D. L., Lehmann, J. R., Weber, M. F., Hatch, G. E. (1989). “Unattenuated structural and biochemical alterations in the rat lung during functional adaptation to ozone.” *Am. Rev. Respir. Dis.* 140: 493-501.

USDA (2009). 2007 Census of Agriculture (AC-07-A-5). National Agricultural Statistics Service. Washington, DC.

Figure 1. Standardized average hourly pieces collected by crop and for all crops




Notes: We standardize average hourly productivity by subtracting the minimum number of pieces per hour required to reach the piece rate regime and dividing by the standard deviation of productivity for each crop. The vertical line reflects the regime threshold for crossing from the minimum wage to the piece rate regime.

Figure 2. Variation in productivity by worker, all crops

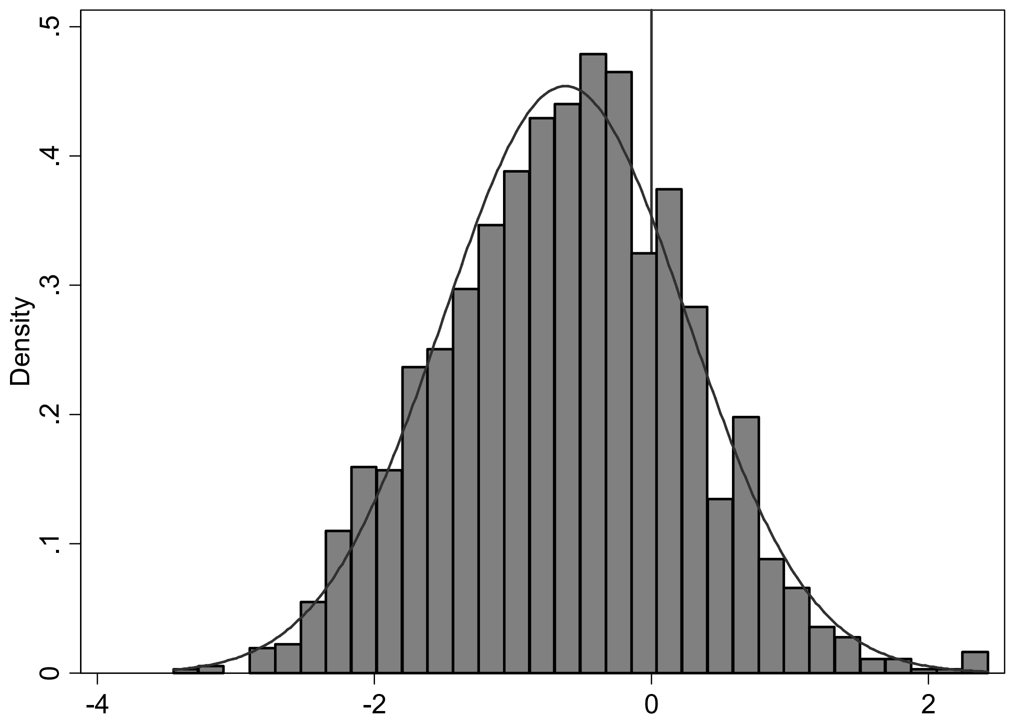


Figure 3. Variation in productivity by day, all crops

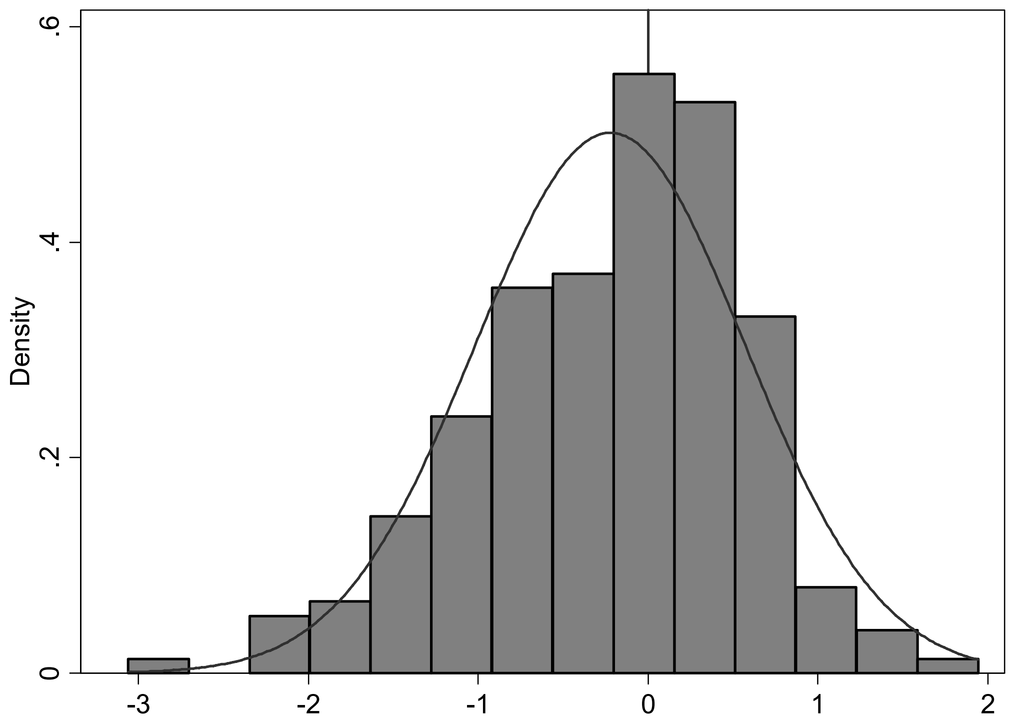


Figure 4. Average demeaned daily ozone and temperature in 2010

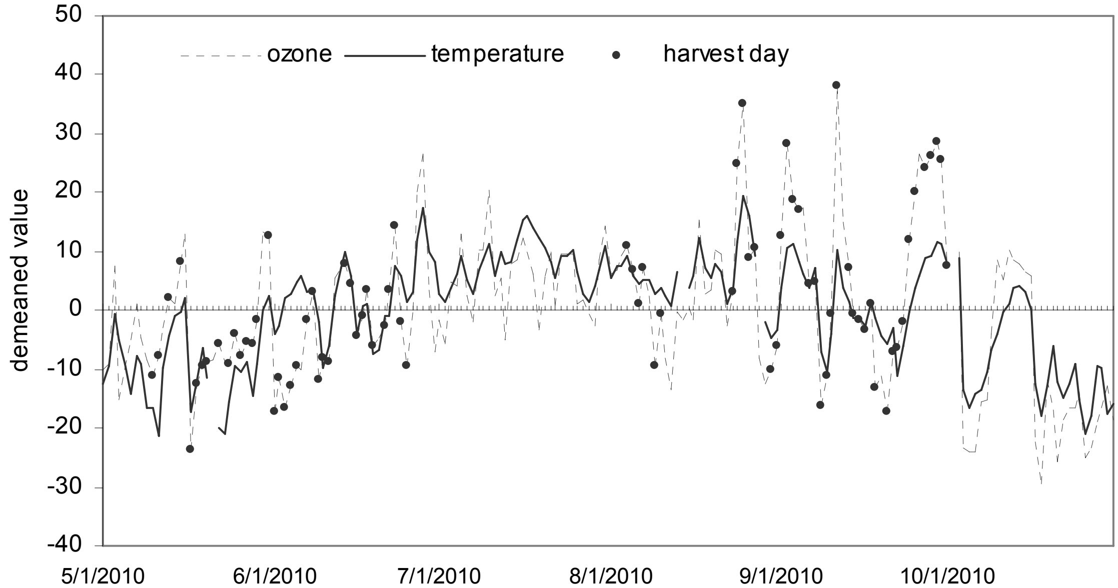


Table 1. Summary statistics

| **A. Productivity variables** (n=36,215) | Observations | mean | SD | SD within worker | SD between workers |
|---|---|---|---|---|---|
| <u>1. Minimum wage regime</u> | | | | | |
| Hourly pieces (crop 1) | 11753 | 2.03 | 0.57 | 0.44 | 0.47 |
| Hourly pieces (crop 2) | 4114 | 3.08 | 0.77 | 0.65 | 0.69 |
| Hourly pieces (crop 3) | 5920 | 2.29 | 0.48 | 0.31 | 0.44 |
| hours worked | 21787 | 7.63 | 1.29 | 0.76 | 1.20 |
| <u>2. Piece rate regime</u> | | | | | |
| Hourly pieces (crop 1) | 3675 | 3.42 | 0.40 | 0.30 | 0.32 |
| Hourly pieces (crop 2) | 5512 | 4.92 | 0.85 | 0.61 | 0.64 |
| Hourly pieces (crop 3) | 5241 | 3.88 | 0.82 | 0.50 | 0.66 |
| hours worked | 14428 | 7.34 | 1.52 | 0.96 | 1.35 |

| **B. Environmental variables** (n=155) | mean | SD | min. | max. |
|---|---|---|---|---|
| ozone (ppb) | 47.77 | 13.24 | 10.50 | 86.00 |
| temperature (F) | 78.15 | 8.52 | 56.30 | 96.98 |
| atmospheric pressure (mb) | 1001.55 | 6.48 | 988.86 | 1012.59 |
| resultant wind speed (mph) | 2.74 | 0.53 | 1.61 | 4.60 |
| solar radiation (W/m2) | 837.33 | 174.07 | 187.00 | 1083.33 |
| relative humidity (%) | 45.33 | 10.04 | 27.90 | 93.50 |
| precipitation (mm) | 2.40 | 5.05 | 0.00 | 35.48 |

| **C. Sample** | |
|---|---|
| total # of dates | 155 |
| total # of employees | 1664 |
| mean # of days with farm | 20 |

Notes: SD: Standard deviation. Crop 1 is time plus all pieces, with a piece rate of $0.5/piece and minimum pieces per hour of 3. Crop 2 is time plus pieces, with a piece rate of $0.3/piece and minimum pieces per hour of 4. Crop 3 is time plus pieces, with a piece rate of $1/piece and minimum pieces per hour of 3.

Table 2. Regression results of the effect of ozone on avoidance behavior

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| | extensive margin: probability(work) | | intensive margin: hours worked | |
| ozone (ppb) | -0.0017 | -0.0018 | 0.0014 | 0.0014 |
| | [0.0020] | [0.0021] | [0.0123] | [0.0125] |
| worker fixed effect | N | Y | N | Y |
| Observations | 39,223 | 39,223 | 36,215 | 36,215 |
| R-squared | 0.11 | 0.16 | 0.24 | 0.27 |

Standard errors clustered on date and worker in brackets. * significant at 10%; ** significant at 5%; *** significant at 1%. All regressions include controls for temperature (quadratic), air pressure, wind speed, solar radiation, relative humidity, precipitation, day of week dummies, month*year dummies, and piece rate contract type dummies. All environmental variables are the mean of hourly values from 6am-3pm.

Table 3. Main regression results of the effect of ozone on productivity

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| ozone (ppb) | -0.0116 | -0.0123 | -0.0092 | -0.0124 |
| | [0.0043]*** | [0.0052]** | [0.0055]* | [0.0058]** |
| model | linear | Tobit | median | censored median |
| Observations | 36215 | 36215 | 36215 | 36215 |
| (Psuedo) R2 | 0.31 | 0.10 | 0.19 | 0.24 |

Standard errors clustered on date and worker in brackets. * significant at 10%; ** significant at 5%; *** significant at 1%. The dependent variable is standardized hourly pieces collected. All regressions include controls for temperature (quadratic), air pressure, wind speed, solar radiation, relative humidity, precipitation, day of week dummies, month*year dummies, and piece rate contract type dummies. All environmental variables are the mean of hourly values from 6am-3pm. Bootstrapped standard errors for both median regressions were obtained using 50 replications.

Table 4. Separation rates by productivity decile

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| | A. Unadjusted productivity | | B. Productivity adjusted for tenure | |
| productivity decile | separation rate | tenure (days) | separation rate | tenure (days) |
| 1 | 0.065 | 12.44 | 0.061 | 17.99 |
| 2 | 0.060 | 15.55 | 0.063 | 19.20 |
| 3 | 0.047 | 16.58 | 0.055 | 18.47 |
| 4 | 0.053 | 18.96 | 0.047 | 19.47 |
| 5 | 0.034 | 18.64 | 0.047 | 21.56 |
| 6 | 0.042 | 21.28 | 0.039 | 22.13 |
| 7 | 0.044 | 21.09 | 0.038 | 19.24 |
| 8 | 0.032 | 22.27 | 0.029 | 18.72 |
| 9 | 0.025 | 23.24 | 0.024 | 19.41 |
| 10 | 0.025 | 24.31 | 0.023 | 18.17 |

This table shows daily mean separation rates and tenure by productivity decile.

Table 5. Sensitivity of regression results of the effect of ozone on productivity

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **A. Linear model** | | | | | | |
| ozone (ppb) | -0.0116 | -0.0097 | -0.0125 | -0.0111 | -0.0129 | -0.0136 |
| | [0.0043]*** | [0.0041]** | [0.0045]*** | [0.0050]** | [0.0048]*** | [0.0052]*** |
| R-squared | 0.31 | 0.53 | 0.31 | 0.33 | 0.32 | 0.33 |
| | | | | | | |
| **B. Tobit model** | | | | | | |
| ozone (ppb) | -0.0123 | -0.0105 | -0.0121 | -0.0130 | -0.0146 | -0.0154 |
| | [0.0052]** | [0.0049]** | [0.0053]** | [0.0059]** | [0.0057]** | [0.0064]** |
| Pseudo R-squared | 0.10 | 0.31 | 0.10 | 0.11 | 0.12 | 0.13 |
| | | | | | | |
| model | baseline | worker fixed effect | include min. and max. of temp. (quadratic) and solar rad. | include min. and max. of temp. (indicators) and solar rad. | exclude obs. .1 SD of regime threshold | exclude obs. .2 SD of regime threshold |
| Observations | 36215 | 36215 | 36215 | 36215 | 32415 | 30239 |

Standard errors clustered on date and worker in brackets. * significant at 10%; ** significant at 5%; *** significant at 1%. The dependent variable is standardized hourly pieces collected. All regressions include controls for temperature (quadratic; except column 4, which includes indicator variables for every 5 degrees F), air pressure, wind speed, solar radiation, relative humidity, precipitation, day of week dummies, month*year dummies, and piece rate contract type dummies. All environmental variables are based on hourly values from 6am-3pm.

Table 6. Regression results of the effect of lagged ozone on productivity

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| **A. Linear model** | | | | | |
| ozone (ppb) | -0.011 | -0.013 | -0.013 | -0.016 | -0.015 |
| | [0.004]*** | [0.005]*** | [0.005]*** | [0.005]*** | [0.005]*** |
| 1 lag ozone (ppb) | | | -0.004 | | -0.006 |
| | | | [0.004] | | [0.006] |
| 2 lag ozone (ppb) | | | | | 0.003 |
| | | | | | [0.005] |
| R-squared | 0.31 | 0.32 | 0.32 | 0.32 | 0.32 |
| | | | | | |
| **B. Tobit model** | | | | | |
| ozone (ppb) | -0.012 | -0.013 | -0.012 | -0.016 | -0.014 |
| | [0.005]** | [0.006]** | [0.006]** | [0.006]*** | [0.006]** |
| 1 lag ozone (ppb) | | | -0.003 | | -0.003 |
| | | | [0.005] | | [0.007] |
| 2 lag ozone (ppb) | | | | | 0.001 |
| | | | | | [0.005] |
| Pseudo R-squared | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| | | | | | |
| Day(s) of week excluded | none | Monday | Monday | Monday & Tuesday | Monday & Tuesday |
| Observations | 35465 | 25456 | 25456 | 17498 | 17498 |

Standard errors clustered on date and worker in brackets. * significant at 10%; ** significant at 5%; *** significant at 1%. The dependent variable is standardized hourly pieces collected. All regressions control for temperature (quadratic), air pressure, wind speed, solar radiation, relative humidity, precipitation, day of week dummies, month*year dummies, and piece rate contract type dummies. All environmental variables are the mean of hourly values from 6am-3pm.