Environmental Stress, Lactation, and Production: Evidence from Dairy Industry

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Abstract

Recent estimates of ambient ozone effects on agriculture mainly focuses on the crop production sector, and the negative role that ozone plays in the dairy industry has been largely disregarded. Relying on an IV-based causal inference framework, this study provides the first causal estimate of the ozone effects on the lactational performance of dairy cows and the corresponding behavioral responses of dairy farmers. We find that elevated ozone concentrations significantly shorten lactation period length, and such ozone-induced adjustment in lactation period length is attributable to the ozone-induced reduction in milk yield and ozone-induced elevation in somatic cell counts. According to our estimations, the avoided losses in total milk output from a one-ppb and two-ppb reduction in ozone concentrations are equivalent to approximately 0.65% and 1.28% of the dairy sector's industrial revenues in Wisconsin. This highlights the necessity for subsidies on dairy farmers' use of air ventilation systems with activated carbon filters and points to the need for more stringent pollution-management legislation aimed at ozone.

Keywords: Agriculture; Ambient ozone; Dairy production; Lactation; Pregnancy exposure

JEL Classification: I10; Q15; Q18; Q51; Q53

1 Introduction

Different from ozone in the stratosphere, which protects life from ultraviolet radiation, surface-level ozone is a pollutant that reduces global crop production (Tai et al., 2014) and accounts for thousands of premature deaths (Madronich, 2014). Formed by the photochemical reaction between volatile organic compounds (VOCs) and nitrogen oxides (NO_X) (Edwards et al., 2014; Deschenes et al., 2017), ozone at the surface-level is highly concentrated in the summer season, yet there are also reports on high ozone concentrations during wintertime in the U.S. (Schnell et al., 2009; Edwards et al., 2014). Ozone pollution has a deep impact on societies, as it poses threats on food security (McGrath et al., 2015), human health (Janke, 2014; Wang et al., 2022), and public security (Burkhardt et al., 2019).

Accounting for one percent of the U.S. gross domestic product, the dairy industry serves a strong role in ensuring employment and economic growth (Xinhua, 2019). Cow milk and dairy products are important sources of dietary calcium intake (Black et al., 2002), which attains height and benefits bone health (Willett and Ludwig, 2020; Black et al., 2002). Despite the threats posed by ozone pollution and the strong role served by the dairy industry, the linkage between these two is largely unexplored. In this study, we estimate the causal ozone effects on the lactational performance of dairy cows and the corresponding behavioral responses of dairy farmers to such an observed change in the lactational performance.

Surface-level ozone pollution damages human health mainly through metabolic disorder (Miller et al., 2016) and systemic inflammation (Peden et al., 1995; Kim et al., 2011). These mechanisms also apply to dairy cows, as cows share the exact same biomarkers through which ozone hurts human (Beaupied et al., 2022). Metabolic disorder and systemic inflammation, in turn, could decrease milk yield (Edwards and Tozer, 2004; Huzzey et al., 2015). Nonetheless, since ozone is an invisible pollutant (Wang et al., 2022), the awareness of ozone pollution is low. Quantifying the ozone effects on lactational performance helps raise both policy makers and dairy farmers' awareness of ozone hazards, which could reduce the adverse effects of ozone pollution on dairy production.

The lactational performance is a crucial factor in determining when to dry off a cow; it is recommended that dairy farmers should dry off a cow when its milk return is lower than the marginal cost of feed, care, and labor (O'Connor and Oltenacu, 1998). The rearrangement in drying off, however, might not always take place in practice because of potential obstacles that dairy farmers may encounter. Hence, it is vital to understand the extent to which dairy farmers rearrange the optimal dry-off day in response to the change in lactational performance induced by ozone pollution, which helps reveal the potential benefits from such behavioral responses.

Wisconsin's comparatively high levels of ozone and low levels of particulate-matter concentrations provide us with a good opportunity to explore the harmful ozone effects on lactation. This study takes advantage of the detailed Wisconsin cow lactation record from the Council on Dairy Cattle Breeding (CDCB), one of the most exhaustive lactation records in the U.S. The lactation record contains detailed information on the dairy herd and the location, birth date, calving date, number of days in milk per lactation cycle for each dairy cow. By matching the cow lactation record to the rich environmental factors, including air pollution and weather conditions, retrieved from the National Aeronautics and Space Administration (NASS) and the European Centre for Medium-Range Weather Forecasts (ECMWF), we are able to identify the linkage between exposure to ozone pollution and dairy production in Wisconsin.

Identification for the causal effect of ozone exposure on cows' lactational performance and dairy farmers' behavioral responses could be challenging due to omitted-variable biases and classical measurement errors. Omitted-variable biases could be led by ZIP-specific, time-dependent associations between ozone pollution and lactation. Classical measurement errors could be attributable to the fact that ozone exposure is assigned to individual cows from satellite grid cells, which could bias the magnitude of OLS estimates downward (Currie and Neidell, 2005; Arceo et al., 2016; Schlenker and Walker, 2016; Deschenes et al., 2020).

We leverage ozone spread from upwind neighbor locations, within a particular distance range, as an instrumental variable to address these empirical challenges (Liu et al., 2023; Liu and Lu, 2023a, 2023b, 2024; Lu, 2023; Wang et al., 2022). Surface-level ozone could be transmitted by wind from upwind locations (Cox et al., 1975; Wang et al., 2001; Kato et al., 2004; Wang et al., 2022), suggesting that upwind ozone is predictive to local ozone concentrations. More importantly, ozone transmitted from upwind locations within a certain distance range is presumably an exogenous shock to the lactational performance and the milk production process, supporting its validity as an instrumental variable.

Relying on this IV-based causal inference framework, we provide the first causal estimate of the ozone effects on the lactational performance and lactation period length of dairy cows. We find that an additional-ppb of ozone during pregnancy significantly shortens the lactation period by 2.43%, and this ozone-induced adjustment in lactation period length is attributable to the milk-yield reduction and somatic-cell-count elevation induced by elevated ozone concentrations. Our predictions suggest that the total milk production in Wisconsin is predicted to increase by 1.68 billion lb. and 3.35 billion lb. when ambient ozone concentrations decrease by 0.5 standard deviation and 1 standard deviation, respectively. These averted losses in milk production are equivalent to approximately 0.32 and 0.63 billion USD in monetary values, accounting for around 0.65% and 1.28% of the industrial revenues in Wisconsin's dairy sector.

Further analyses on heterogeneity demonstrate that exposure to elevated ozone has smaller adverse effects on the first lactation cows and young cows, and that the lactational performance is primarily harmed by ozone exposure in the second and third pregnancy trimesters, rather than the first.

This study contributes to the literature in the following three ways. First, it adds to the large body of literature assessing how the lactational performance of dairy cows responds to environmental stressors, including heat stress (Bernabucci et al., 2014, 2015; Polsky and von Keyserlingk, 2017; Li et al., 2021), vibration (Gygax and Nosal, 2006), wildfire smoke (Anderson et al., 2022), overcrowding (Bach et al., 2008), and water salinity (Solomon et al., 1995). Despite the rich literature on the lactational effects of various environmental stressors, the effects of surface-level ozone pollution remain largely unexplored, and only Beaupied et al. (2022) assesses the association between ozone pollution and milk production using data from three dairy herds. Different from Beaupied et al. (2022), this study estimates the causal effects of ozone pollution on the lactational performance of dairy cows by employing a causal inference framework. Using an instrumental variable based on the wind-driven long-distance spread of ozone from neighbor locations, this study commits to establishing a causal linkage between ambient ozone and dairy productivity.

Second, it contributes to the emerging literature assessing the health effects of pregnancy exposure to pollution. The extant literature has focused primarily on the effects of pregnancy exposure to pollution on birth outcomes of humans, including exposure to air pollution (Currie et al., 2009), microcystin in blue-green algae (Jones, 2019a), lead from mineral mining (Von der Goltz and Barnwal, 2019), and lead in drinking water (Dave and Yang, 2022). Despite the emerging literature focusing on birth outcomes, the health effects of pregnancy exposure to pollution on women post-partum are largely neglected; only Von der Goltz and Barnwal (2019) discuss how blood post-partum in women post-partum responds to lead pollution from mineral mining. Similarly, the lactational response to pollution exposure during pregnancy has been overlooked due to the potential privacy concerns in recording women's breastfeeding data. Cows and humans share a few similarities in pregnancy. First, as humans, most cows have singleton pregnancy with a gestation period of nine months (Amat et al., 2022). Second, the placental microbiota found in cows are analogous to their counterparts in humans (Hummel et al., 2022). Hence, this study also sheds some light on the human health effects of pregnancy exposure to pollution.

Third, it adds to the growing literature assessing the behavioral responses and the potential adaptations to the agricultural production change induced by environmental stresses. The existing literature has focused on the behavioral responses in crop production to the environment (Aragón et al., 2021; Bareille and Chakir, 2023; Burke and Emerick, 2016; Costinot et al., 2016; Cui, 2020a, 2020b; Cui and Tang, 2023; Cui and Zhong, 2023; Chen and Gong, 2021; Obembe et al., 2021), and studies discussing the behavioral responses in dairy production are scarce (Berman, 2011; Key and Sneeringer, 2014). Motivated by a concise conceptual framework, we empirically test the extent to which dairy farmers respond to the ozone-induced milk-yield reduction and somatic-cell-count elevation, which provides the first empirical evidence on the behavioral responses of dairy farmers to ambient ozone exposure.

The rest of the study is organized as follows. Section 2 includes a concise conceptual model characterizing how dairy farmers shorten the lactation period in response to the ozone-induced change in dairy productivity and somatic-cell-count-management costs. Section 3 presents the empirical challenges and identification strategy. Section 4 describes the data.

Section 5 shows the main results and conducts a welfare analysis. Section 6 discusses heterogeneity and Section 7 concludes.

2 Conceptual Model

A representative dairy farmer maximizes her total profit by determining when to dry off a cow.[1] Specifically, a dairy farmer would dry off a cow if the marginal return of milking is lower than the marginal cost in the current lactation (O'Connor and Oltenacu, 1988). We assume that this representative dairy farmer is a price taker, and the milk price is p. The total output of milk is indexed by Y, which is affected by the number of days in milk indexed by t and ozone exposure indexed by o. Similarly, the total cost (R) associated with managing somatic-cell counts, a reflection of mastitis, is also affected by the number of days in milk and ozone exposure. We let c denote the per-day cost, in additional to somatic-cell-count management, during the lactation period. For simplicity, we assume that the dry period is fixed and index the total cost during the dry period by S. The profit maximization problem is written as

$$\max_t \pi = pY(t;o) - R(t;o) - ct - S. \tag{2.1}$$

Given that the relationship between the per-day milk yield and the number of days in milk follows an inverted-U shape, the total milk production is an increasing, concave function of the number of days in milk, as illustrated in Panel B of Figure 1. We hence assume the total milk production Y increases with the number of days in milk t at a decreasing rate, suggesting that $\frac{\partial Y}{\partial t} > 0$ and $\frac{\partial^2 Y}{\partial t^2} < 0$. We assume that $\frac{\partial Y}{\partial o} < 0$ and $\frac{\partial^2 Y}{\partial t \partial o} < 0$, characterizing that milk production decreases with ozone and that higher ozone concentrations reduces milk yields on the marginal

[1] This conceptual model is based on Cui (2020a) and Liu and Lu (2023a).

day in milk. In addition, as depicted in Panel B of Figure 1, we assume that the total cost associated with somatic-cell-count management R increases with the number of days in milk t at an increasing rate, implying that $\frac{\partial R}{\partial t} > 0$ and $\frac{\partial^2 R}{\partial t^2} > 0$. We also assume that $\frac{\partial R}{\partial o} > 0$ and $\frac{\partial^2 R}{\partial t \partial o} > 0$, characterizing that the total costs associated with somatic-cell-count management increases with ozone and that higher ozone concentrations elevate somatic cell counts on the marginal day in milk. By solving this profit maximization problem and deriving the first order condition, we find that the representative dairy farmer would maximize her profit when

$$\pi_t\big(t^*(p,o)\big) \equiv p\frac{\partial Y}{\partial t} - \frac{\partial R}{\partial t} - c = 0. \tag{2.2}$$

This conceptual model predicts how the length of lactation period is affected by the ozone-induced changes in both dairy productivity and somatic-cell-count-management costs. Total differentiating equation (2.2) with respect to o generates the following equation:

$$p\frac{\partial^2 Y}{\partial t^2}\frac{dt}{do} + p\frac{\partial^2 Y}{\partial t \partial o} - \frac{\partial^2 R}{\partial t^2}\frac{dt}{do} - \frac{\partial^2 R}{\partial t \partial o} = 0. \tag{2.3}$$

Rearranging equation (2.3) gives us the following comparative statics:

$$\frac{dt^*}{do} = \frac{\frac{\partial^2 R}{\partial t \partial o} - p\frac{\partial^2 Y}{\partial t \partial o}}{p\frac{\partial^2 Y}{\partial t^2} - \frac{\partial^2 R}{\partial t^2}} < 0. \tag{2.4}$$

Given that equation (2.4) has a positive numerator and a negative denominator, this comparative statics suggests that the optimal number of days in milk is negatively affected by ozone pollution. That is, dairy farmers are expected to shorten the lactation period in response to the ozone-induced lactational performance change to maximize their profits. Motivated by this conceptual model, the remainder of this study will evaluate the extent to which elevated ozone harms lactational performance and the extent to which dairy farmers respond to such an ozone-induced loss in lactational performance.

3 Data

3.1 Cow Lactation

We obtain the cow lactation record from the CDCB,[2] which is one of the most exhaustive lactation records in the U.S. The lactation record contains detailed information on the dairy herd and the corresponding ZIP-code area, birth date, calving date, number of days in milk per lactation cycle for each cow. The milk yield and somatic cell score (SCS) of each cow are recorded approximately once a month. We calculate the somatic cell counts (SCC) using SCS in the record following the formula $SCC = 2^{SCS-3} \times 100{,}000$ (Norman et al., 2022). We also compute the peak milk yield, the average milk yield, the trough SCC, and the average SCC for each cow in each lactation cycle. Table 1 summarizes the aforementioned key variables. As shown in Table 1, the average length of lactation period is around 333 days in our data sample, which covers 557,403 cows located at 376 ZIP-code areas in Wisconsin over the time period of 2012–2022.

To investigate how ozone exposure affects the shape of the yield function and the SCC function over the lactation period, We construct two curvature indices: the curvature at the peak point of the yield function and the curvature at the trough point of the SCC function. As illustrated in Panel A of Figure 1, both yield and SCC are approximately quadratic functions of the number of days in milk. Hence, for each cow in each lactation period, we fit a yield quadratic polynomial and a SCC quadratic polynomial of the number of days in milk. We then extract the coefficients on the linear and the quadratic terms of these two polynomials and compute the first and second derivatives. The next step is to use the following formula (Stewart et al., 2020), a

[2] For more details, see https://redmine.uscdcb.com/projects/cdcb-customer-service/wiki/Format_4.

formula commonly seen in calculus, to compute the curvatures at the peak point of the yield function and the trough point of the SCC function:

$$\kappa = \frac{|f''(x)|}{(1 + [f'(x)^2])^{\frac{3}{2}}}, \tag{3.1}$$

where $f(x)$ represents a yield or a SCC quadratic polynomial of the number of days in milk. The curvature at the peak point of the yield function measures how fast yield is changing from increase to decrease upon reaching the peak point of the yield function; the curvature at the trough point of the SCC function measures how fast SCC is changing from decrease to increase upon reaching the trough point of the SCC function.

3.2 Ozone Pollution

Three-hourly data on surface-level ozone concentrations are obtained from the Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA-2) released by the NASS.[3] We interpolate the ozone data from grid cells to ZIP-code areas and then average to the month level. Specifically, referring to Fenske and Kala (2015) and He et al. (2016), we interpolate the ozone data on four grid cells nearest to the centroid of each ZIP-code area using the inverse-weighted distance method. Briefly speaking, grid cells closer to the ZIP-code area centroid are assigned more weights, and grid cells far from the centroid are assigned less weight. We do not use ozone pollution data recorded by monitoring stations, as they are mostly located in metropolitan areas, while dairy herds are mainly located in rural areas. As shown in Table 1, the average ozone concentrations in Wisconsin over the study period is around 31.30 ppb. Figure

[3] The dataset is accessible at https://disc.gsfc.nasa.gov/datasets/M2I3NVCHM_5.12.4/summary?keywords=inst3_3d_chm_Nv. We choose the grid option NLDAS-2 with a resolution of 0.125°×0.125°.

A2 depicts the correlation between monthly ozone concentrations constructed from both the EPA, recorded by the monitoring stations, and from the MERRA-2, tracked by the remote-sensing satellite, suggesting a high R-squared between the two data sources.

3.3 Weather Conditions

Hourly data on weather conditions are obtained from the fifth generation ECMWF atmospheric reanalysis data (ERA5) released by the ECMWF with a grid resolution of 0.1° × 0.1°.[4] Using the same inverse-distance weighted method, we interpolate the weather data on four nearest grid cells to the centroid of each ZIP-code areas. The weather variables we obtain from ERA5 include u-component of wind, v-component of wind, temperature, dewpoint temperature, net solar radiation, and surface atmospheric pressure. Following Ostrenga (2019), wind speed and wind direction are calculated using the u-component and the v-component of wind speed. Thermal-heat index (THI) is computed following the formula (National Research Council, 1971):

$$THI = \left(0.55 \times T_{db} + 0.2 \times T_{dp}\right) \times 1.8 + 32 + 17.5, \quad (3.2)$$

where T_{db} is the surface-level temperature expressed in Celsius degree and T_{dp} is the dew-point temperature in Celsius degree. To account for potential non-linear effects of weather conditions on cow lactation, we include the second-degree polynomials of each weather variables.

4 Empirical Strategy

4.1 Panel Fixed Effects Model

[4] The dataset is accessible at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview.

We first rely on a panel fixed effects model to explore the impact of ozone exposure on the length of lactation period and the lactational performance. The fixed effects regression equation is constructed as

$$Y_{izym} = \beta_0 + \beta_1 P_{izym}^{preg} + \beta_2 P_{izym}^{lac} + \boldsymbol{W}_{izym}^{preg}\gamma_1 + \boldsymbol{W}_{izym}^{lac}\gamma_2 + \delta_i + \theta_{cm} + \vartheta_{ym} + \varepsilon_{izym}, \quad (4.1)$$

where Y_{izym} denotes the outcome variables (the length of lactation period in logarithm, the mean and peak milk yields in logarithms over the lactation period, the mean and trough SCCs in logarithms over the lactation period, and the two aforementioned curvature indices) of cow i locating at ZIP-code area z and calving at month m of year y.

The primary explanatory variables are P_{izym}^{preg} and P_{izym}^{lac}, referring to the exposure in pregnancy and exposure in lactation to ambient ozone for cow i locating at ZIP-code area z and calving in month m of year y.[5] $\boldsymbol{W}_{izym}^{preg}$ and $\boldsymbol{W}_{izym}^{lac}$ refer to weather conditions during pregnancy and lactation period for cow i locating at ZIP-code area z and calving in month m of year y, including the quadratic polynomials of wind speed, THI, net solar radiation, and surface pressure.

The baseline specification includes the individual (δ_i), the county-by-month (θ_{cm}), and the month-by-year (ϑ_{ym}) fixed effects. The individual fixed effects (δ_i) capture time-invariant cow attributes that affect lactation, including the baseline health status of cows. Since more than 98% of the cows in our data sample have stayed in the same herds over the entire sample period, the individual fixed effects also absorb herds-specific time-persistent characteristics that affect lactation. The county-by-month fixed effects (θ_{cm}) absorb any seasonal correlation between ozone exposure in pregnancy and lactation, and such a correlation is allowed to vary by county.

[5] The average concentration of ozone pollution over the preceding nine months prior to calving. For instance, if the calving date of a cow is November 20, 2015, then the ozone exposure in pregnancy is computed as the average concentration of ozone from March 2015 to November 2015 in that ZIP-code area.

The month-by-year fixed effects (ϑ_{ym}) absorb any statewide common shocks varying across time, such as improvements in feeding technology. The error term is denoted by ε_{izym}. Standard errors in the baseline estimation are clustered at the individual and county-by-year levels (Cameron et al., 2011), which allows for autocorrelation within each cow across time and autocorrelation across cows calving in the same year within the same county.

4.2 2SLS Model

The main empirical challenges for identifying the causal impact of ozone exposure on dairy productivity and dairy farmers' behavioral responses include omitted-variable biases and classical measurement errors. Omitted-variable biases could potentially be led by ZIP-specific, time-dependent associations between ozone and lactation. Surface-level ozone is a type of secondary air pollutant formed by nitrogen oxides (NO_x) and volatile organic compounds (VOCs) (Deschenes et al., 2017), and NO_x is mostly emitted by industrial facilities (Fowlie et al., 2012), which could also be a source of other types of pollutants. If these pollutants have detrimental effects on dairy productivity, OLS estimates could be biased downward.

Classical measurement errors could potentially be led by the fact that ozone pollution exposure is assigned to individual cows from satellite grid cells, and the smallest geographic unit in our data sample is ZIP-code area, which could bias OLS estimates downward as well (Currie and Neidell, 2005; Arceo et al., 2016; Schlenker and Walker, 2016; Deschenes et al., 2020).

To overcome the aforementioned empirical challenges and identify the causal effect of ozone exposure in pregnancy on dairy productivity and farmers' behavioral responses, we rely on a two-stage least squares (2SLS) model. In particular, we construct an instrumental variable (IV) given the fact that surface-level ozone pollution can be spread by wind from upwind neighbor ZIP-code areas to downwind ZIP-code areas (Cox et al., 1975; Kato et al., 2004; Wang et al., 2001, 2022). Studies constructing IVs based on the wind-driven long-distance spread of air pollutants include Bayer et al. (2009), Chen et al. (2021), Deryugina et al. (2019), and Wang et al. (2022).

Our goal is to construct an IV that is predictive of local ozone concentrations, while it has to be an exogenous shock to cows' health and lactation. Referring to Wang et al. (2022), Lu (2023), Liu et al. (2023), Liu and Lu (2023a, 2023b, 2024), we employ ozone spread from upwind ZIP-code areas located within a 100–200 km radius of the focal ZIP-code area as an IV for the following two reasons. First, the instrument relevance criterion is satisfied, as ozone from upwind neighbor ZIP-code areas is transmitted to the focal ZIP-code area by wind (Cox et al., 1975; Kato et al., 2004; Wang et al., 2001, 2022), suggesting that upwind ozone is presumably predictive to ozone concentrations in the focal location. Since upwind ozone too far from the focal ZIP-code area may not be successfully transmitted by wind, we restrict the outer radius range as 200 km following Wang et al. (2022).

Second, the exclusion restriction criterion is also satisfied, as we exclude upwind ozone from neighbor ZIP-code areas located within 100 km of the focal ZIP-code area when constructing the IV (Chen et al., 2021). Ozone spread from neighbor ZIP-code areas too close to the focal ZIP-code area may be formed by NO_x emitted from the same industrial facility, directly affecting the health and lactation of cows located in the focal ZIP-code area. It is therefore important to exclude neighbor ZIP-code areas too close to the focal ZIP-code area when constructing the IV.

The IV is constructed as follows. As depicted in Figure 2, let b denote the wind vector and let c denote the vector connecting a neighbor ZIP-code area within the 100–200 km radius band, indexed by n, to the focal ZIP-code area, indexed by f. The angle formed between vector b and the east direction is denoted by α, and the angle formed between vector c and the east direction is denoted by θ. We assign a weight to each neighbor ZIP-code area located within the 100–200 km radius band using the following formula (Wang et al., 2022; Liu et al., 2023; Liu and Lu, 2023a, 2023b, 2024; Lu, 2023):

$$w_{nf} = \frac{\frac{cos(\theta_{nf} - \alpha_{nf})}{d_{nf}} \cdot \mathbf{1}\{cos(\theta_{nf} - \alpha_{nf}) > 0\}}{\sum_{k=1}^{m} \frac{cos(\theta_{kf} - \alpha_{kf})}{d_{kf}} \cdot \mathbf{1}\{cos(\theta_{kf} - \alpha_{kf}) > 0\}}, \quad (4.2)$$

where d_{nf} represents the distance between a neighbor ZIP-code area n and the focal ZIP-code area f. Note that this weight assigned to each neighbor ZIP-code area located within the 100–200 km radius band excludes any ZIP-code areas in which wind does not blow towards the focal ZIP-code area. The next step is to compute the ozone concentrations spread from upwind neighbor ZIP-code areas within the radius band for each focal ZIP-code area by summing the product of weight assigned to each neighbor ZIP-code areas and ozone concentrations at each neighbor ZIP-code areas. Since it takes time for ozone to be spread from upwind neighbor ZIP-code areas to focal ZIP-code area, we sum ozone spread from upwind ZIP-code areas over the preceding week to account for such a time lag following Wang et al. (2022) and further average it over the nine-month pregnancy.

The updated empirical model after instrumenting for ozone is as follows.

$$P_{izym}^{preg} = \alpha_0 + \alpha_1 I_{izym}^{preg} + \alpha_2 I_{izym}^{lac} + \boldsymbol{W}_{izym}^{preg}\gamma_1 + \boldsymbol{W}_{izym}^{lac}\gamma_2 + \delta_i + \theta_{cm} + \vartheta_{ym} + \eta_{izym}, \quad (4.3)$$

$$P_{izym}^{lac} = \alpha_0 + \alpha_1 I_{izym}^{preg} + \alpha_2 I_{izym}^{lac} + \boldsymbol{W}_{izym}^{preg}\gamma_1 + \boldsymbol{W}_{izym}^{lac}\gamma_2 + \delta_i + \theta_{cm} + \vartheta_{ym} + \eta_{izym}, \quad (4.4)$$

$$Y_{izym} = \beta_0 + \beta_1 \widehat{P_{izym}^{preg}} + \beta_2 \widehat{P_{izym}^{lac}} + \boldsymbol{W}_{izym}^{preg}\gamma_1 + \boldsymbol{W}_{izym}^{lac}\gamma_2 + \delta_i + \theta_{cm} + \vartheta_{ym} + \varepsilon_{izym}, \quad (4.5)$$

where equations (4.3) and (4.4) represent the first stages of the 2SLS model, and equation (4.5) represents the second stage. The instrumental variables are denoted by I_{izym}^{preg} and I_{izym}^{lac}, which are the average ozone concentrations spread from upwind ZIP-code areas during pregnancy and lactation period. The meaning of the remaining variables stays the same as of model (4.1).

5 Results

5.1 Baseline Results

Table 2 reports the estimates of the impact of ambient ozone on the length of lactation period and the lactational performance. The dependent variables in Columns (1)–(7) are the logarithmic length of lactation period, the logarithmic mean yield, the logarithmic peak yield, the curvature at the peak point of yield curve, the logarithmic mean SCC, the logarithmic trough SCC, and the curvature at the trough point of SCC curve, respectively. Panel A presents the OLS estimates, while Panel B shows the 2SLS estimates where ozone is instrumented by ozone spread from upwind ZIP-code areas within the 100–200 km radius band. All specifications in Panels A and B include the cow FE, the county-by-month FE, the month-by-year FE, and weather controls.

Several crucial findings arise from the baseline results. First, recall that ambient ozone during both pregnancy and lactation period are included in the model. Their point estimates in Table 2 indicate that overall, ozone exposure during lactation period does not affect the lactation length and lactational performance significantly. By contrast, cows' lactation length and lactational performance are significantly influenced by ambient ozone during pregnancy. This result is supported by the fact that mammary growth,[6] measured by the total amount of mammary

[6] Mammary growth is a crucial determinant of milk production (Davis, 2017).

DNA, mainly occurs in pregnancy and declines throughout lactation (Capuco et al., 2001; Davis, 2017). The rest of the empirical analyses will hence focus on the effects of ozone exposure during pregnancy.

Second, we find a statistically significant effect of ozone exposure during pregnancy on the length of lactation period. Column (1) indicates that a 1 ppb increase in average ozone concentrations during pregnancy shortens the lactation period by 2.43%. In line with the expectation from our conceptual model, ozone pollution induces dairy farmers to dry off cows earlier in response to its damages on lactational performance, which will be discussed later.

Third, Columns (2)–(7) suggest a consistent finding that ozone exposure during pregnancy hurts the lactational performance. Columns (2) and (3) indicate that a one ppb increase in ozone concentrations during pregnancy decreases the mean milk yield and the peak milk yield by 5.17% and 5.13%, respectively. Analogously, Columns (5) and (6) show that a one ppb rise in ozone concentrations increases the mean SCC and the peak SCC by 14.68% and 16.33%, respectively. Additionally, ozone pollution also affects the shape of the yield curve and the SCC curve. Columns (4) and (7) indicate that ozone exposure during pregnancy significantly increases both the curvature at the peak point of the yield curve and the curvature at the trough point of the SCC curve; the point estimates on curvatures suggest that milk yield decreases faster upon reaching the peak point and that SCC increases faster upon reaching the trough point.

Fourth, Panel C of Table 2 shows a strong first-stage relationship. The point estimate is statistically significant at the 1% level, suggesting that the instrument relevance criterion is satisfied. Additionally, above the Stock-Yogo critical threshold (Stock and Yogo, 2005), the high Kleibergen-Paap F-statistic in Table 2 signifies that the ozone spread from upwind ZIP-code areas is not a weak IV.

Fifth, comparing the magnitude of the OLS estimates and the 2SLS estimates, we find that the OLS estimates in Panel A are smaller in magnitude compared to the 2SLS estimates in Panel B. The discrepancy in magnitude between OLS estimates and 2SLS estimates shows the importance of using an IV, and such a discrepancy could be primarily explained by the aforesaid classical measurement errors (Arceo et al., 2016; Currie and Neidell, 2005; Deschenes et al., 2020; Schlenker and Walker, 2016). Additionally, as discussed in the empirical strategy section, omitted variables could potentially bias the OLS estimates either upward or downward, which may also contribute to such a discrepancy.

5.2 Robustness Checks

Table B1–B3 discuss the robustness of the baseline results. We first check the robustness of the baseline results to additional weather conditions and additional pollutants, as additional weather conditions and pollutants may be correlated with ambient ozone, which could still potentially bias the estimated effects. Different from the baseline estimation in Panel A, which controls for wind speed, solar radiation, surface atmospheric pressure, and THI, Panel B further controls for wind direction and precipitation and Panel C further controls for PM_{10}, SO_2, NO_2, and CO. As shown in Panels B and C, the results are robust after further controlling for these weather and pollutant variables.

We next show the robustness of the baseline results to alternative fixed effects and alternative clustering levels. The baseline specification, replicated in Panel A, includes the cow, the county-by-month, and the month-by-year fixed effects, which capture time-invariant cow attributes, any county-varying seasonal correlation between ozone exposure and lactation, and any statewide common shocks varying across time. Keeping the individual and month-by-year fixed effects, Panel D replaces the county-by-month fixed effect by ZIP-by-month fixed effects, which allows the ozone-lactation seasonal correlation to vary by ZIP-code areas. The results reported in Panel D are qualitatively similar to the baseline results, though the significance level of some of the estimated effects has changed. Further, instead of clustering the error term at the cow and county-by-year levels, Panel E clusters the error term at the cow and ZIP-by-year levels, which allows for autocorrelation within each cow across time and autocorrelation across cows calving in the same year within the same ZIP-code area. The results in Panel E, with alternative clustering levels, are highly similar to the baseline results.

We then test the robustness of the baseline results to using several different methods to construct the IV. First, recall the baseline specification relies on equation (4.2) to construct upwind ozone, in which only wind direction is considered. Given that wind speed may also matter, Panel F modifies equation (4.2) and takes account of the role of wind speed in ozone transmission, which writes as follows (Wang et al., 2022):

$$w_{nf} = \frac{\frac{cos(\theta_{nf} - \alpha_{nf})}{d_{nf}} \cdot \mathbf{1}\{cos(\theta_{nf} - \alpha_{nf}) > 0\} \cdot \text{speed}_n}{\sum_{k=1}^{m} \frac{cos(\theta_{kf} - \alpha_{kf})}{d_{kf}} \cdot \mathbf{1}\{cos(\theta_{kf} - \alpha_{kf}) > 0\} \cdot \text{speed}_k}. \tag{5.1}$$

Second, following Wang et al. (2022), the baseline specification assumes that it approximately takes a week for ozone to be transmitted to the focal county by wind. Given that the transmission speed may vary under different scenarios, this one-week transmission time is only a rough estimate. Panels F and G relax this assumption by specifying the transmission time as six days and eight days, respectively. Third, as indicated by equation (4.2), we rely on the cosine terms to exclude non-upwind neighbor counties; the angle formed by the wind vector and the vector pointing toward the focal county, indexed by b and c, determines whether a neighbor county is upwind. The baseline specification defines a neighbor county as upwind if the angle formed by vectors b and c is less than 90°. Alternatively, Panels I and J define the upwind angle as 45° and 60°, respectively, to test the robustness to this angle specification. As shown in Table B2, all results using different IV construction methods are qualitatively similar to the baseline results.

Lastly, Table B3 shows the results using alternative ozone metrics. The baseline specification, replicated in Panel A, relies on average ozone concentrations, assuming a linear ozone effect on lactation and a homogeneous ozone effect for both daytime and nighttime exposure. Alternatively, to check whether daytime exposure, the primary time for feeding and milking, drives the ozone effect on lactation, Panels K and L relax this assumption by limiting the time window to 9:00–15:59 and 8:00–19:59 (Aakre et al., 2018; Liu and Lu, 2023a; Lu, 2023; Tai et al., 2014). Additionally, to test whether the main finding that elevated ozone concentrations shorten the lactation period and hurt the lactational performance still holds when average ozone is replaced by cumulative ozone metrics, Panels M and N rely on AOT40 and W126, which is computed as follows (Liu and Lu, 2023a; Lu, 2023; McGrath et al., 2015):

$$AOT40 = \sum_h O_h\,, where\ O_h = \begin{cases} O_h - 40, O_h > 40 \\ 0, otherwise \end{cases}; \tag{5.2}$$

$$W126 = \sum_h (O_h \frac{1}{1 + 4403e^{-126 \cdot O_h}}). \tag{5.3}$$

In equations (5.2) and (5.3), O_h refers to the ozone concentration at hour h. Weighting less or ignoring low concentrations, these two cumulative metrics assume that the estimated ozone effects on lactation are driven by high-dose exposure to ambient ozone. As shown in Table B3, the main finding that elevated ozone shortens the lactation period and hurts the lactational performance holds well with alternative ozone metrics.

5.3 Welfare Analysis

The empirical results show that elevated ozone concentrations negatively affect the lactational performance of dairy cows. What does the adverse ozone effect on the lactational performance imply to the real world? Estimating the averted losses in milk production from ozone control enables environmental policy makers to carry out more comprehensive cost-benefit evaluations and helps dairy farmers determine the most appropriate mitigation strategies. Based on the estimated ozone effect on milk yields, this section conducts a welfare analysis by predicting the increments in milk production under the simulated scenarios that ambient ozone concentrations decrease by 1 ppb (0.5 standard deviation) and 2 ppb (1 standard deviation), respectively, in Wisconsin.

The procedures for simulated predictions are as follows. First, we simulate two scenarios that ambient ozone concentrations reduced by 1 ppb and 2 ppb. Specifically, we reduce the mean of ozone in our sample by 1 ppb and 2 ppb, while maintaining the data distribution, and bootstrap 100 times to get the simulated ozone data (Liu and Lu, 2023a). We then leverage the simulated datasets to estimate the ozone effect on milk yield using the baseline specification equation (4.5) with 100 repetitions (Mandelman, 2013). Next, based on the coefficients of interest estimated using the simulated ozone data and the statistics drawn from the USDA (2023),[7] we calculate the average benefit in milk production per cow herd and the total benefit in milk production for Wisconsin from ozone pollution management.

The simulated predictions on the average milk production benefits per cow herd from ozone control, in terms of both lb. and monetary values, are presented in Figure 3A. When ambient ozone concentrations decrease by 1 ppb and 2 ppb, the average annual milk production

[7] According to the statistics from the USDA (2023), there are 6,572 cow herds, composed of 1,274,000 heads of cows, in Wisconsin. The annual milk production per cow is 24,889 lb. The milk price is 0.1880 USD per lb. All statistics are from 2021.

per cow herd is predicted to increase by 255,180 lb. and 510,280 lb., respectively. According to the USDA (2023), the milk price is 0.1880 USD per lb. in Wisconsin. These increments in milk production are hence equivalent to around 47,970 USD and 95,930 USD in monetary values. These benefits suggest that it may be worthwhile for dairy farmers to install air ventilation systems with activated carbon filters, which have been demonstrated to be effective in lowering ambient ozone concentrations in the air (Fisk, 2009).

The simulated-prediction results on the total milk production benefits from ozone control in Wisconsin are reported in Figure 3B. As ambient ozone concentrations decrease by 1 ppb and 2 ppb in Wisconsin, the state-wide total milk production is predicted to increase by 1.68 billion lb. and 3.35 billion lb., respectively. These predicted increments in state-wide total milk production are equivalent to approximately 0.32 and 0.63 billion USD in monetary values, as demonstrated in Panels II and IV of Figure 3B. Based on a back-of-the-envelope calculation, these saved milk production values account for around 0.65% and 1.28% of the industrial revenues in Wisconsin's dairy sector,[8] which should be factored into the cost-benefit analyses of pollution management conducted by Wisconsin policymakers and legislators.

6 Heterogeneity

6.1 Heterogeneity Across Lactation Cycles and Ages

Our previous empirical results do not take account of heterogeneity in how exposure to ambient ozone affects lactation length and lactational performance. A large strand of literature

[8] The dairy industry contributes 45.6 billion USD (49.12 billion in 2021 USD) to the industrial revenues in Wisconsin. More details are accessible at https://economicdevelopment.extension.wisc.edu/articles/the-contributions-of-agriculture-to-the-wisconsin-economy-an-update-for-2017/.

has demonstrated that calves and young cattle are protected against diseases by antibodies from colostrum, and such a transfer of passive immunity is effective in reducing morbidity and elevating growth rates (Furman-Fratczak et al., 2011; Mason et al., 2022; Pardon et al., 2015). Similar to humans, part of the protection by the transfer of passive immunity gradually disappears as time goes on. Further, older cows have a higher exposure risk to mastitis pathogens and longer infections resulting in extensive tissue damage (Reneau, 1986). These findings suggest that younger cattle tend to be healthier and more protected against external stresses.

This section analyzes the heterogeneous ozone effects on lactation length and lactational performance across lactation cycles and age groups. The total lifespan for commercial dairy cows range from 4.5 to 6 years, with the first calving time at around 2 years of age (De Vries and Marcondes, 2020). Based on this fact, we assess the heterogeneity for the first lactation cows vs. the second or later lactation cows and for cows aged less than 2.5 years vs. 2.5 or more years. Specifically, we interact the ozone variables with an indicator variable ($\mathbf{1}_{izym}^{1st}$) for the first lactation cows and an indicator variable ($\mathbf{1}_{izym}^{2.5y}$) for cows aged less than 2.5 years, respectively. The second stage equation of the 2SLS model to estimate the heterogeneous ozone effects on lactation length and lactation performance is written as follows, where ϕ_2 and ϕ_5 are the coefficients of interest:

$$Y_{izym} = \beta_0 + \phi_1 \widehat{P_{izym}^{preg}} + \phi_2 \widehat{P_{izym}^{preg}} \times \mathbf{1}_{izym}^{1st} + \phi_3 \mathbf{1}_{izym}^{1st} + \phi_4 \widehat{P_{izym}^{lac}} + \phi_5 \widehat{P_{izym}^{lac}} \times \mathbf{1}_{izym}^{2.5y} + \phi_6 \mathbf{1}_{izym}^{2.5y} + \boldsymbol{W}_{izym}^{preg} \gamma_1 + \boldsymbol{W}_{izym}^{lac} \gamma_2 + \delta_i + \theta_{cm} + \vartheta_{ym} + \varepsilon_{izym}. \quad (6.1)$$

Panels A and B of Table 3 present the heterogeneous ozone effects on lactation period length and lactational performance across lactation cycles and across age groups, respectively. In line with the aforementioned expectations, both Panels A and B show consistent results that exposure to elevated ozone has smaller adverse effects on the lactation period length and lactational performance for the first lactation cows and cows aged less than 2.5 years. Specifically, an additional-one-ppb ambient ozone during pregnancy decreases the lactation period length by 2.27% and the mean yield by 4.90% for the second or later lactation cows, but such decreases are 0.19 percentage points (pp) and 0.43 pp smaller in magnitude for the first lactation cows. Similarly, an additional-one-ppb ozone during pregnancy decreases the lactation period length by 2.33% and the mean yield by 4.83% for cows older than 2.5 years of age, but such decreases are 0.21 pp and 0.32 pp smaller in magnitude for cows aged less than 2.5 years.

6.2 Heterogeneity Across Pregnancy Trimesters

Our baseline empirical analysis does not take into account the heterogeneity in exposure to ambient ozone across different trimesters of pregnancy. It has been demonstrated that the second and third trimesters of pregnancy, rather than the first trimester, are highly correlated with milk secretion after parturition. For instance, hormones involved in the onset of milk secretion do not increase until the second trimester of pregnancy (Convey, 1974). The buildup of colostrum through milk acini and the expansion and dilation of the ductal system occur during the second and the third pregnancy trimesters, respectively (Alex et al., 2020; Jones, 2019b).

To examine whether there exists heterogeneity on the ozone-induced injury on dairy cows' lactation, this section estimates the impact of ozone pollution on the lactation length and the lactational performance of cows across three trimesters of pregnancy. Specifically, we revise the baseline 2SLS equation (4.5) and include the trimester measures of ozone, the average ozone concentrations over each trimester of pregnancy, in the model. The first, second, and third trimesters are referred as $s = 1$, $s = 2$, and $s = 3$, respectively. Other specification remains the same as model (4). The updated model is written as

$$Y_{izym} = \beta_0 + \sum_{s=1}^{3} \beta_1^s \widehat{P_{izym}^s} + \sum_{s=1}^{3} \boldsymbol{W}_{izym}^s \gamma^s + \beta_2 \widehat{P_{izym}^{lac}} + \boldsymbol{W}_{izym}^{lac} \gamma_2 + \delta_i + \theta_{cm} + \vartheta_{ym} + \varepsilon_{izym}. \quad (6.2)$$

Estimated ozone effects on lactation period length and lactational performance across pregnancy trimesters are reported in Figure 4. Each figure presents point estimates on $\beta_1^{s=1}$, $\beta_1^{s=2}$, and $\beta_1^{s=3}$, corresponding to the first, second, and third trimesters of pregnancy. Panel A of Figure 4 suggests that ozone exposure in the last two trimesters significantly induce dairy farmers to dry off cows early, while ozone exposure in the first trimester has no significant impact on the lactation length. This finding is supported by the heterogenous effects of ozone on the lactational performance across trimesters of pregnancy. In line with the early dry-off decision induced by ozone, Panels B–G show that ozone exposure in the first trimester has no significant impact on dairy cows' lactational performance, and this finding is consistent with the aforementioned fact that only the second and third pregnancy trimesters are highly correlated with milk secretion after parturition.

7 Conclusions

The recent literature on ozone effects on agriculture focuses primarily on the crop production sector, and the negative role that ambient ozone plays in the dairy industry has been disregarded to a great extent. Relying on an IV-based causal inference framework, this study provides the first causal estimate of the ozone effects on the lactational performance and lactation period length of dairy cows. We find that elevated ozone concentrations significantly hurt lactational performance and shorten lactation period length. Specifically, a one-ppb rise in ozone concentrations during pregnancy significantly shortens the lactation period by 2.43%.

Such ozone-induced adjustment in lactation period length is attributable to the ozone-induced reduction in milk yield and ozone-induced elevation in somatic cell counts. Response heterogeneity across lactation cycles, age groups, and pregnancy trimesters suggests the complexity in ozone damage to lactation. Further welfare analysis shows that as ozone concentrations decrease by 1 ppb and 2 ppb in Wisconsin, the state-wide total milk production is predicted to increase by 1.68 billion lb. and 3.35 billion lb., respectively. These predicted increments in total milk production are equivalent to approximately 0.32 and 0.63 billion USD in monetary values, accounting for around 0.65% and 1.28% of the industrial revenues in Wisconsin's dairy sector.

This study has a couple of policy implications. First, air ventilation systems with activated carbon filters have been demonstrated being effective in lowering ambient ozone concentrations in the air (Fisk, 2009). Given the large economic benefits of lowering ozone concentrations in dairy production, Wisconsin agricultural policy makers may consider subsidizing dairy farmers' use of air ventilation systems with activated carbon filters. Second, previous cost-benefit evaluations of ozone management have concentrated mostly on human health and crop production. Our findings suggest that the averted losses on dairy production should also be taken into consideration by environmental legislators, pointing to the need for more stringent pollution-management legislation aimed at ozone in Wisconsin or at a larger scale.

This study also has some limitations. First, owing to data limitation, this study focuses on dairy cows in Wisconsin, a leading milk-producing state. Caution is needed in extrapolating the findings of this study to other species (i.e. dairy goats) and other states because of potential genetic variations and milking-practice differences. Second, given that our dataset does not contain information about when dairy cows are removed from dairy farms and sold to the commodity market, we are unable to identify the ozone effects on the culling decisions, which could be another responsive behavior of dairy farms. Future research on the ozone-induced culling decisions is needed for understanding such a behavioral response.

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Environmental Stress, Lactation, and Production: Evidence from Dairy Industry

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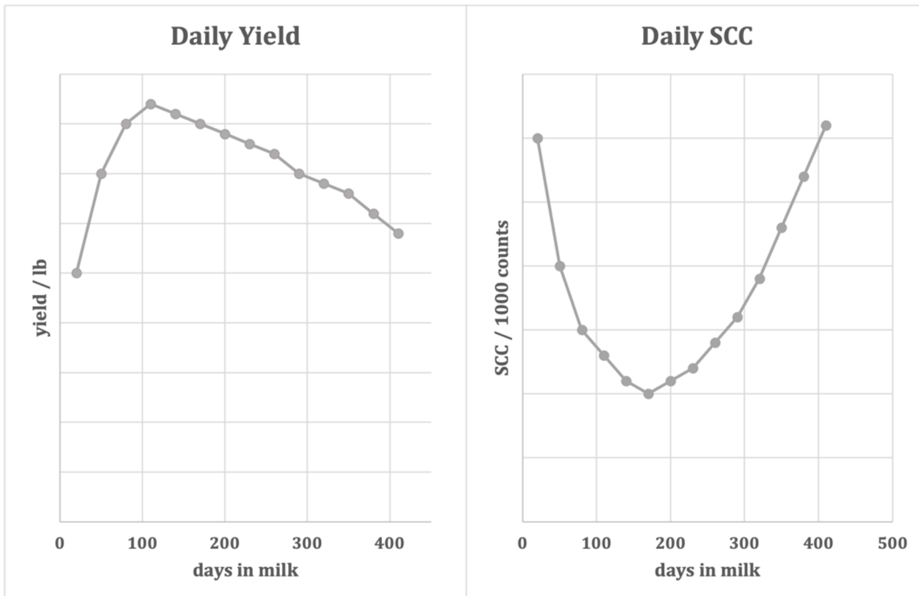
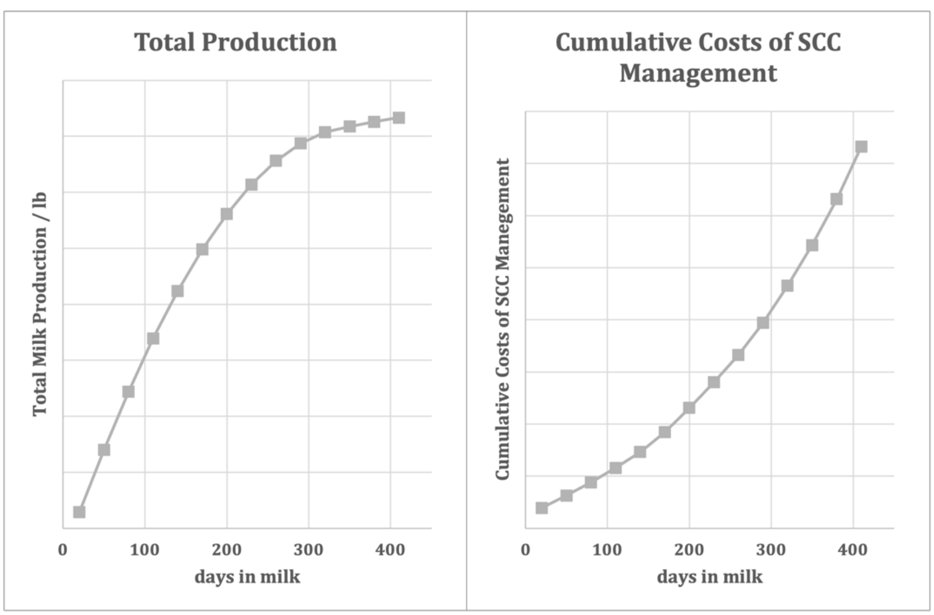
Figure 1 Sample Plots



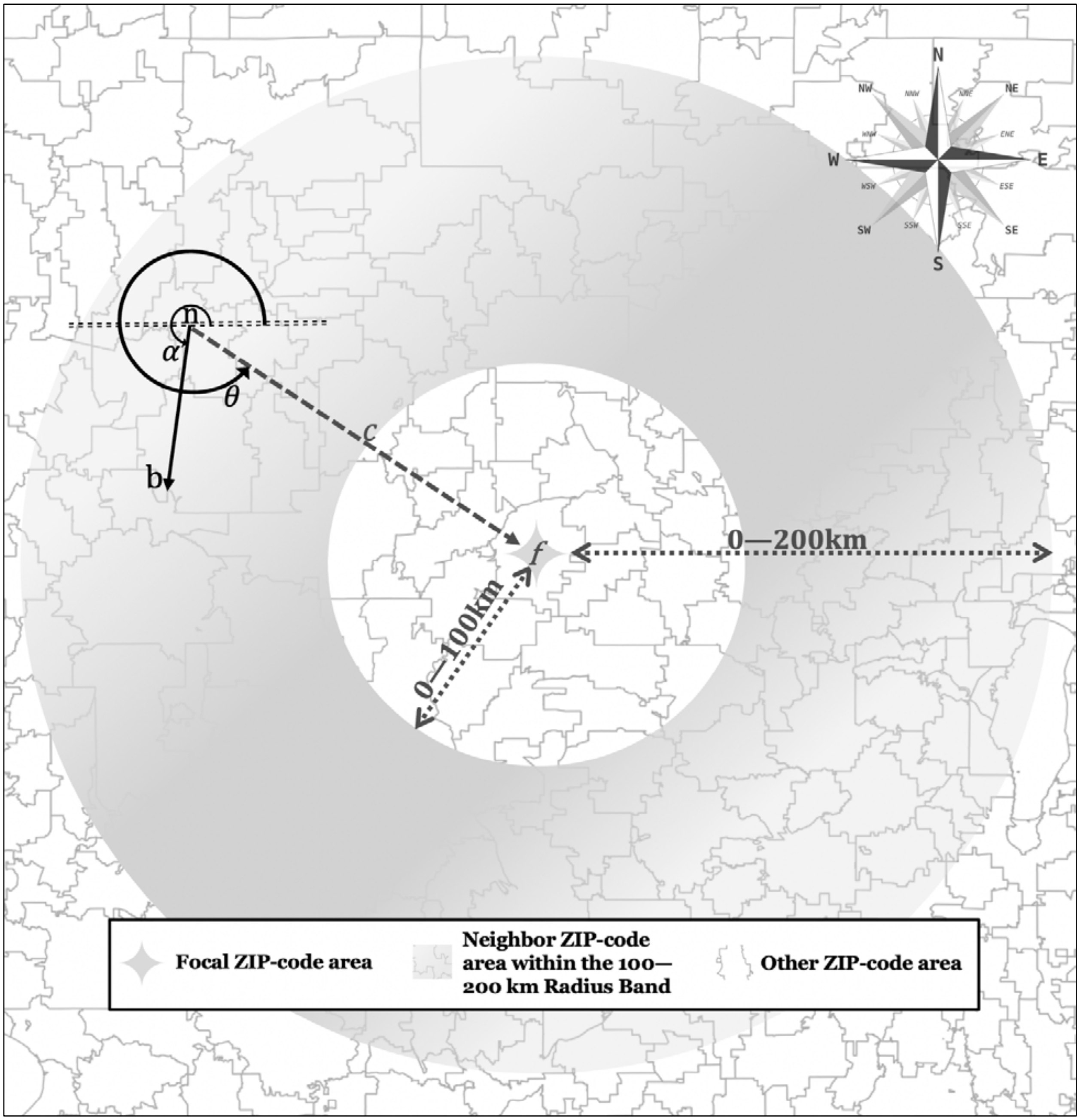
Panel A: Daily Milk Yield and SCC



Panel B: Total Milk Production and Cumulative Costs Associated with SCC Management

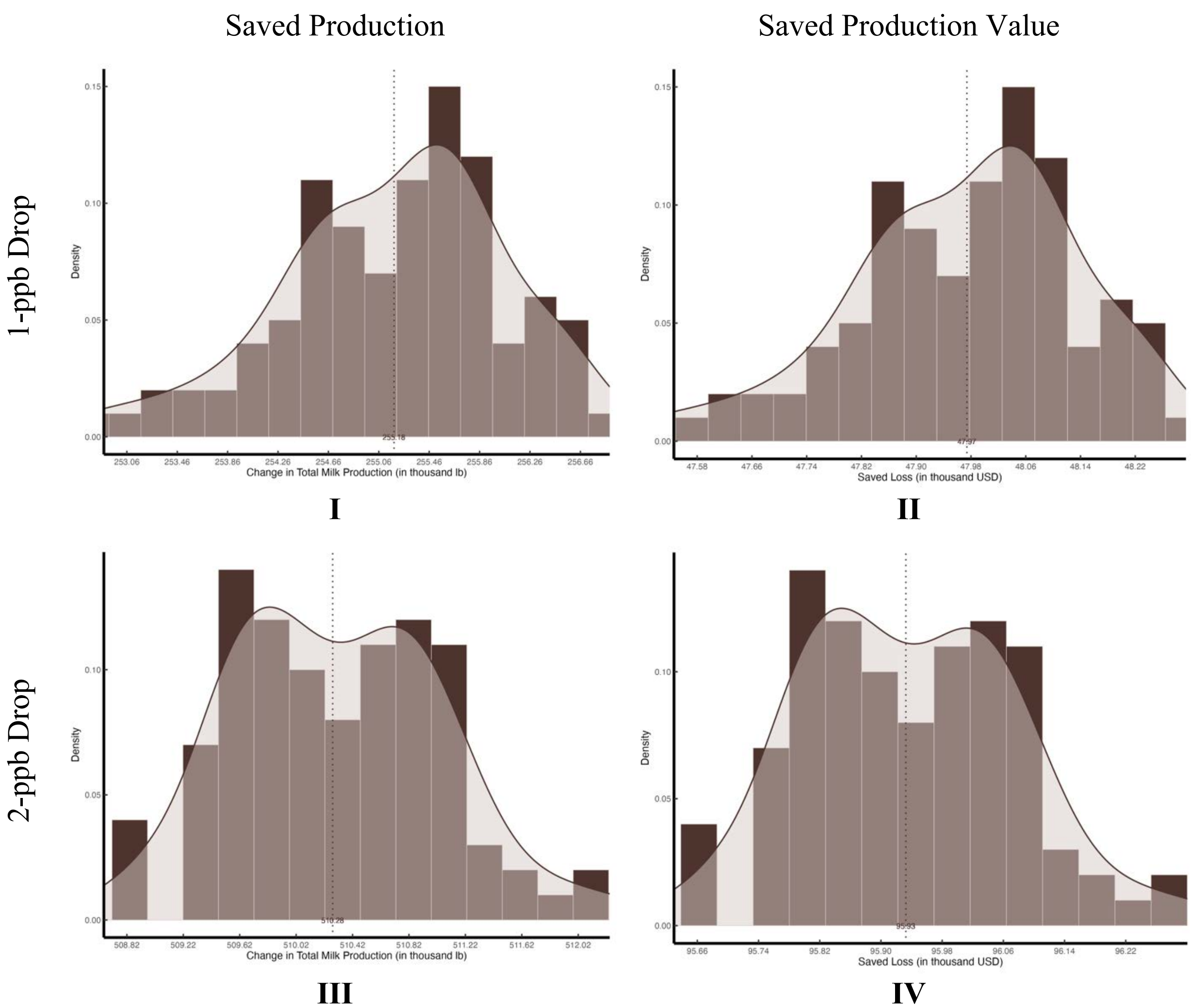
Notes: These plots are schematic diagrams for illustration purposes only. Panel A depicts the daily milk yield function and the daily SCC function of number of days in milk. Panel B depicts the total milk production function and the cumulative SCC-management cost function of number of days in milk.

Figure 2 Illustration of the IV Strategy



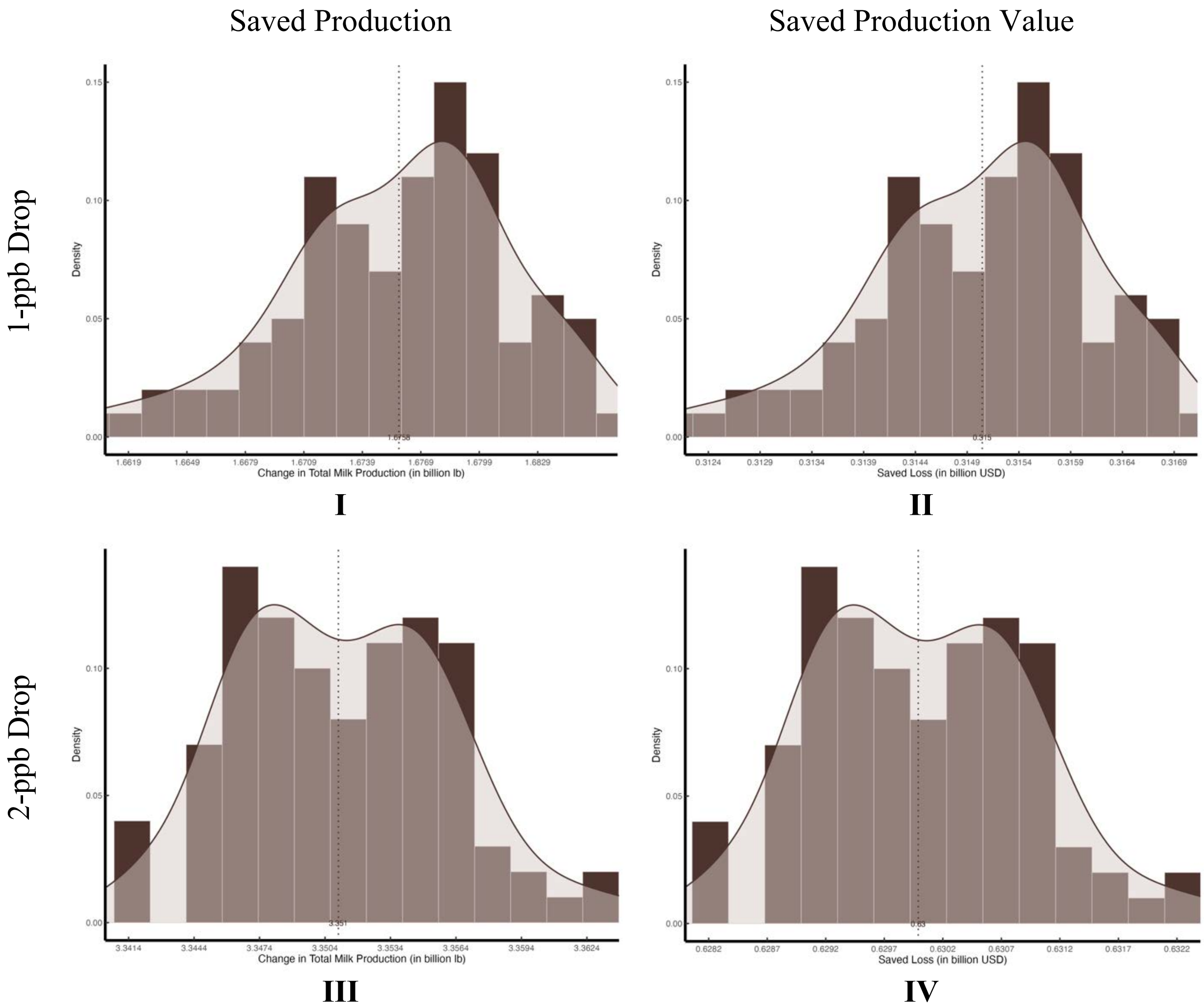
Notes: This plot is a schematic diagram. The arrow b represents the wind vector. The dashed arrow c represents the vector connecting a neighbor ZIP-code area n to the focal ZIP-code area f. The angle between vector b and the east direction is denoted by α. The angle between vector c and the east direction is denoted by θ.

Figure 3A Welfare Analysis per Cow Herd



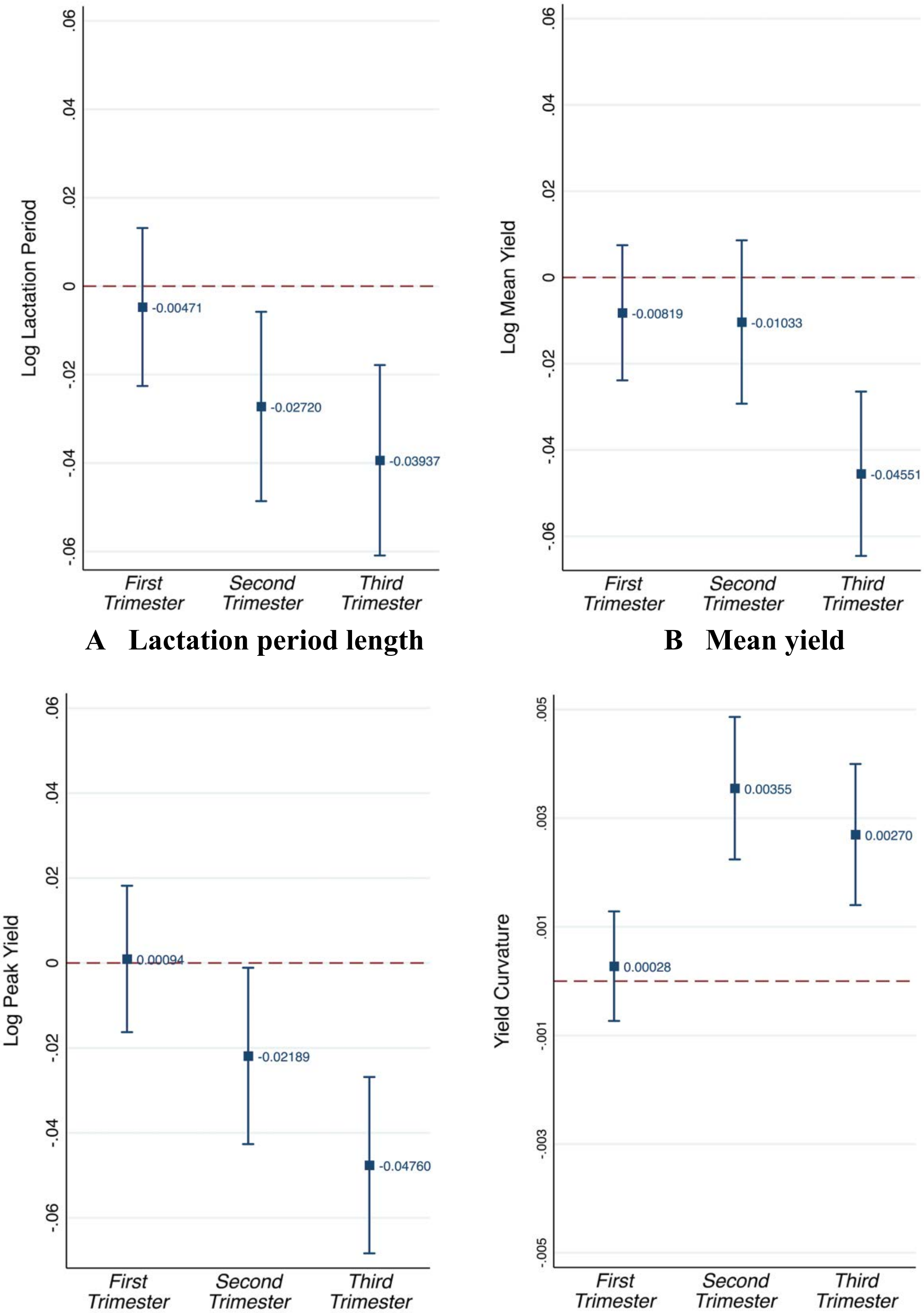
Notes: This figure depicts simulated predictions on the average saved milk production and production value per cow herd from ozone control. Panels I and II are under the scenario of a 1-ppb drop in ambient ozone. Panels III and IV are under the scenario of a 2-ppb drop in ambient ozone.

Figure 3B Welfare Analysis for Wisconsin



Notes: This figure depicts simulated predictions on the state-wide saved milk production and production value in Wisconsin from ozone control. Panels I and II are under the scenario of a 1-ppb drop in ambient ozone. Panels III and IV are under the scenario of a 2-ppb drop in ambient ozone.

Figure 4 Estimates by Trimesters of Pregnancy

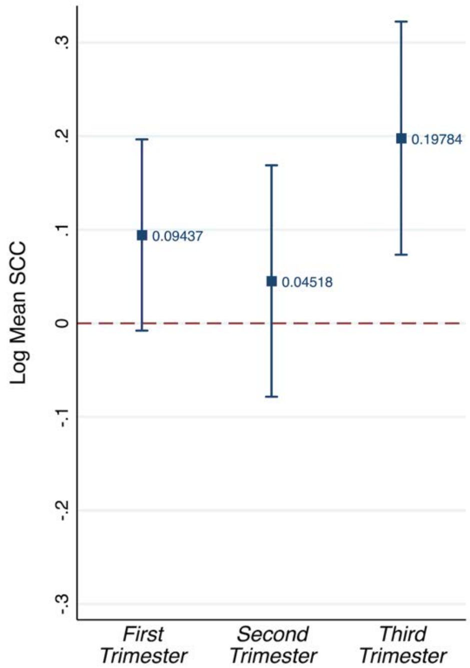


A Lactation period length **B Mean yield**

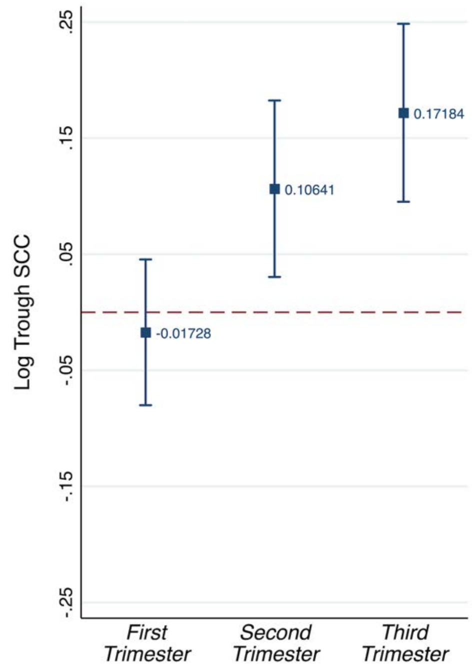
C Max yield **D Yield curvature**

Notes: The error bars represent 90% confidence intervals constructed from standard errors that are two-way clustered at the cow and the county-by-year levels.

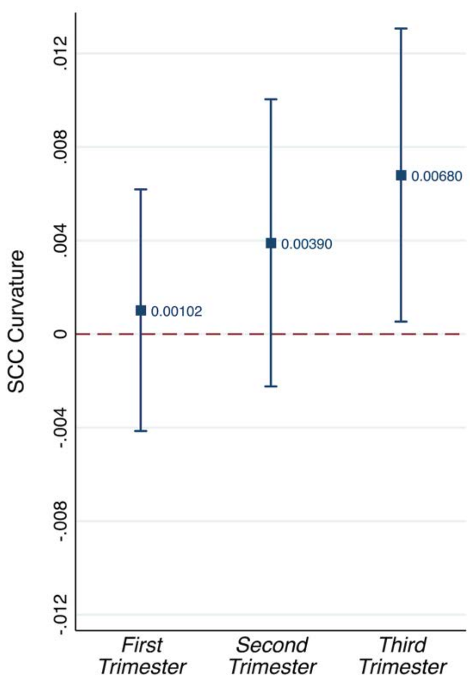
Figure 4 Estimates by Trimesters of Pregnancy (Cont.)



E Mean SCC



F Trough SCC



G SCC curvature

Notes: The error bars represent 90% confidence intervals constructed from standard errors that are two-way clustered at the cow and the county-by-year levels.

Table 1 Summary Statistics

	N	Mean	SD	Min	Max
Panel A: Outcome Variables					
Lactation Period (days)	811,247	333.25978	52.45482	67.00000	626.00000
Mean Yield (lb)	811,247	87.37666	18.13428	2.30000	216.33333
Peak Yield (lb)	811,247	107.76234	24.11347	3.50000	312.00000
Curvature at Peak Point of Yield Function	811,247	0.00286	0.00801	0.00000	0.36161
Mean SCC (1000 cells)	811,247	107.21374	199.71614	12.50000	6,822.51290
Min SCC (1000 cells)	811,247	24.85569	39.48769	12.50000	2,785.76180
Curvature at Trough Point of SCC Function	811,247	0.01641	0.04284	0.00000	0.57918
Panel B: Environmental Factors During Pregnancy					
Ozone (ppb)	811,247	31.29636	1.99948	26.18375	35.86322
Wind Speed (m/s)	811,247	3.14200	0.29249	2.55840	4.89260
Solar Radiation (10^3KJ/m^2)	811,247	3,105.70916	482.68715	2,007.01189	4,486.94716
Surface Pressure (hPa)	811,247	982.26300	5.60797	956.94706	994.99692
THI	811,247	50.56073	4.68569	37.64333	60.52958
Upwind Ozone (100-200 km)	811,247	216.23260	15.49595	145.64019	249.56881
Panel C: Environmental Factors During Lactation					
Ozone (ppb)	811,247	31.15095	1.67975	26.65181	35.27246
Wind Speed (m/s)	811,247	3.13078	0.28246	2.66154	4.81536
Solar Radiation (10^3KJ/m^2)	811,247	3,424.20021	371.06412	2,481.86093	4,671.23155
Surface Pressure (hPa)	811,247	982.35469	5.59807	957.20182	994.80401
THI	811,247	50.31702	3.33549	40.16407	58.10932
Upwind Ozone (100-200 km)	811,247	215.26186	13.64598	151.86351	246.19883

Notes: The data sample includes 557,403 cows located at 376 ZIP-code areas in 60 counties in Wisconsin.

Table 2 Baseline Results

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: OLS	Log Lactation Period	Log Mean Yield	Log Peak Yield	Yield Curvature	Log Mean SCC	Log Trough SCC	SCC Curvature
Ozone (Pregnancy)	-0.01461***	-0.01925**	-0.01872**	-0.00001	0.07003***	0.03899**	0.00217**
	(0.00505)	(0.00764)	(0.00827)	(0.00022)	(0.02706)	(0.01743)	(0.00092)
Ozone (Lactation)	-0.00574	0.00130	-0.00041	-0.00011	0.00316	0.00881	-0.00045
	(0.00464)	(0.00673)	(0.00765)	(0.00020)	(0.02414)	(0.01432)	(0.00088)
Panel B: 2SLS (Second Stage)	Log Lactation Period	Log Mean Yield	Log Peak Yield	Yield Curvature	Log Mean SCC	Log Trough SCC	SCC Curvature
Ozone (Pregnancy)	-0.02432**	-0.05169***	-0.05128***	0.00398***	0.14676**	0.16330***	0.00585*
	(0.01165)	(0.01046)	(0.01148)	(0.00077)	(0.06727)	(0.04154)	(0.00343)
Ozone (Lactation)	0.00190	-0.00926	-0.02199**	0.00054	-0.08794*	0.02856	-0.00032
	(0.00923)	(0.00819)	(0.00905)	(0.00062)	(0.05301)	(0.03288)	(0.00273)
Panel C: 2SLS (First Stage)	Ozone						
Ozone (Pregnancy)	0.01206***						
	(0.00017)						
Ozone (Lactation)	0.01613***						
	(0.00019)						
Observations	811,247	811,247	811,247	811,247	811,247	811,247	811,247
Weather Controls	YES	YES	YES	YES	YES	YES	YES
Cow FE	YES	YES	YES	YES	YES	YES	YES
County-Month FE	YES	YES	YES	YES	YES	YES	YES
Year-Month FE	YES	YES	YES	YES	YES	YES	YES
KP F-Statistics	2722	2722	2722	2722	2722	2722	2722

Notes: Weather controls include the quadratic polynomials of THI, wind speed, surface pressure, and solar radiation. Standard errors are two-way clustered at the cow and county-by-year levels (*** $p<0.01$, ** $p<0.05$, * $p<0.1$).

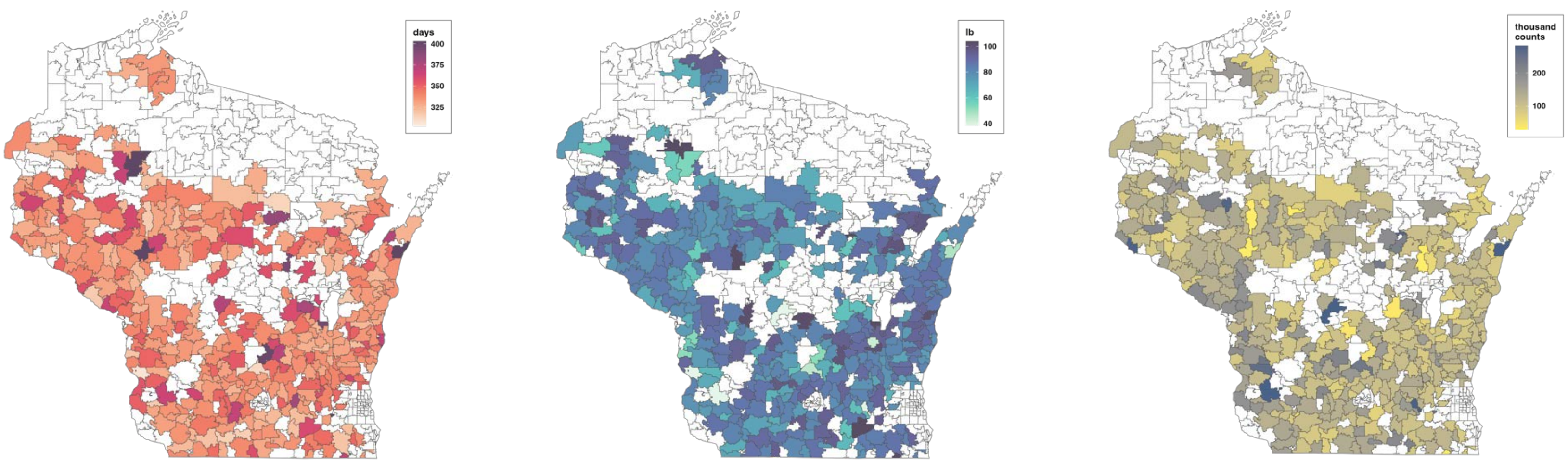
Table 3 Heterogeneity across Lactation Cycles and Ages

	Log Lactation Period (1)	Log Mean Yield (2)	Log Peak Yield (3)	Yield Curvature (4)	Log Mean SCC (5)	Log Trough SCC (6)	SCC Curvature (7)
Panel A: Heterogeneity across lactation cycles							
Ozone during pregnancy	-0.02270*	-0.04904***	-0.04917***	0.00399***	0.14457**	0.15995***	0.005826*
	(0.01165)	(0.00969)	(0.01035)	(0.00077)	(0.06732)	(0.04141)	(0.00343)
$\times \mathbf{1}_{\text{First Lactation}}$	0.00189***	0.00433***	0.00470***	0.00010***	-0.00502***	-0.00959***	0.000004
	(0.00029)	(0.00024)	(0.00026)	(0.00002)	(0.00171)	(0.00105)	(0.00009)
Ozone during lactation	0.00070	-0.01009	-0.02204***	0.00052	-0.08579	0.03038	-0.000328
	(0.00923)	(0.00752)	(0.00808)	(0.00062)	(0.05301)	(0.03275)	(0.00273)
$\times \mathbf{1}_{\text{First Lactation}}$	0.00502***	0.00123***	-0.00287***	0.00005**	-0.00936***	-0.00530***	0.000070
	(0.00037)	(0.00032)	(0.00034)	(0.00002)	(0.00223)	(0.00137)	(0.00011)
KP F-Statistics	1365	1365	1365	1365	1365	1365	1365
Panel B: Heterogeneity across ages							
Ozone during pregnancy	-0.02326**	-0.04828***	-0.04813***	0.00399***	0.14395**	0.15920***	0.00577*
	(0.01165)	(0.00915)	(0.00958)	(0.00077)	(0.06730)	(0.04128)	(0.00343)
$\times \mathbf{1}_{\text{Less than 2.5-year-old}}$	0.00211***	0.00315***	0.00368***	0.00007***	-0.00347**	-0.01070***	0.00014*
	(0.00028)	(0.00022)	(0.00023)	(0.00001)	(0.00166)	(0.00100)	(0.00008)
Ozone during lactation	0.00083	-0.00992	-0.02174***	0.00053	-0.08514	0.03048	-0.00030
	(0.00923)	(0.00712)	(0.00752)	(0.00062)	(0.05301)	(0.03265)	(0.00273)
$\times \mathbf{1}_{\text{Less than 2.5-year-old}}$	0.00521***	0.00113***	-0.00385***	0.00003	-0.01362***	-0.00751***	-0.00006
	(0.00035)	(0.00028)	(0.00030)	(0.00002)	(0.00211)	(0.00127)	(0.00010)
KP F-Statistics	1363	1363	1363	1363	1363	1363	1363
Observations	811,247	811,247	811,247	811,247	811,247	811,247	811,247
Weather Controls	YES	YES	YES	YES	YES	YES	YES
Cow FE	YES	YES	YES	YES	YES	YES	YES
County-Month FE	YES	YES	YES	YES	YES	YES	YES
Year-Month FE	YES	YES	YES	YES	YES	YES	YES

Notes: Weather controls include the quadratic polynomials of THI, wind speed, surface pressure, and solar radiation. Standard errors are two-way clustered at the cow and county-by-year levels (*** p<0.01, ** p<0.05, * p<0.1).

Online Appendix

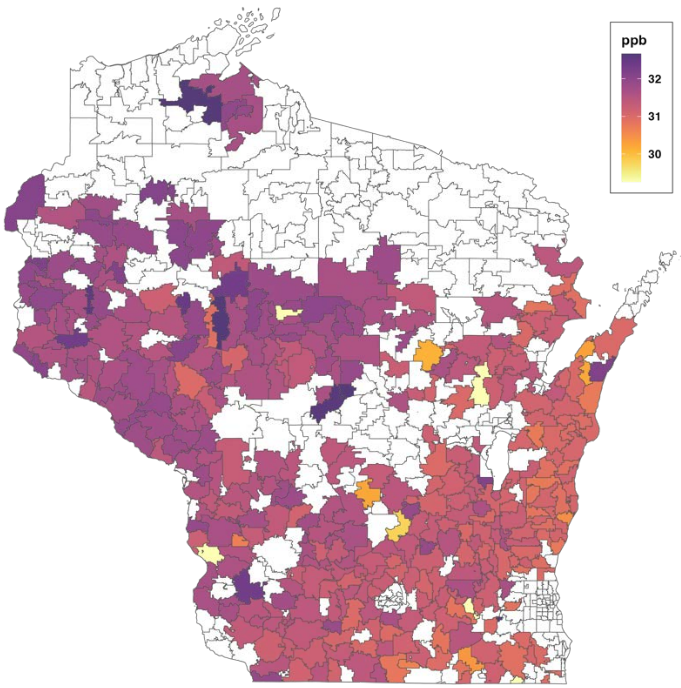
Figure A1 Spatial Distribution of Key Outcome Variables



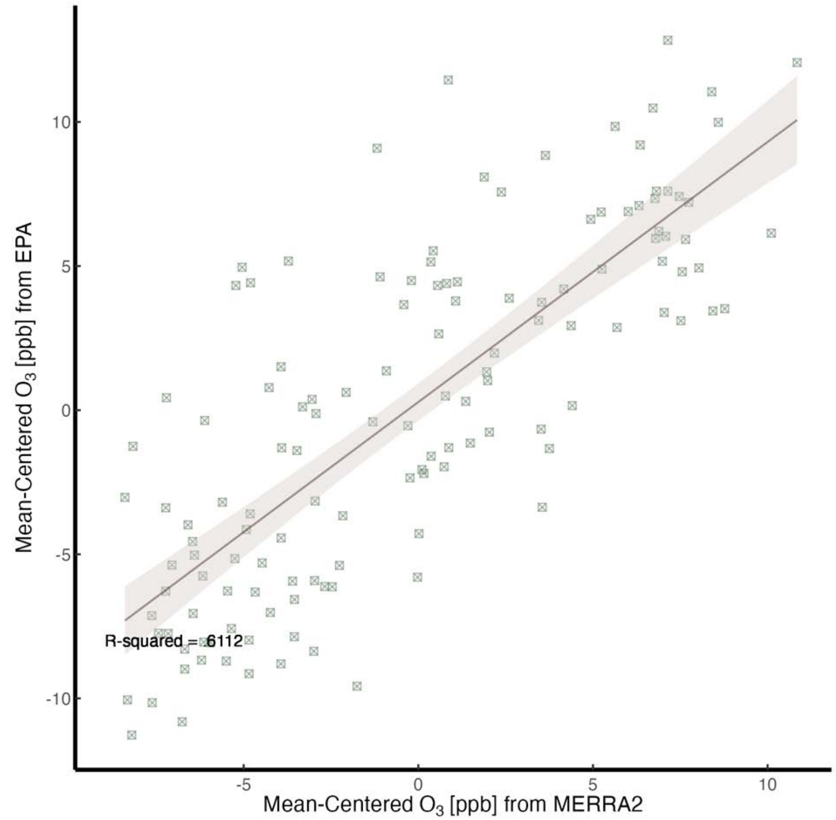
Panel A: Lactation period length **Panel B: Average milk yield** **Panel C: Average SCC**

Notes: The figures depict the spatial distribution of average length of lactation period, average milk yield per day, and average SCCs per day over the study period.

Figure A2 Ambient Ozone Concentrations in Wisconsin



Panel A: Spatial distribution of ozone



Panel B: Correlation between MERRA-2 and EPA

Notes: Panel A depicts the spatial distribution of ozone in Wisconsin. Panel B depicts the correlation of ozone between MERRA-2 and EPA, two different data sources.

Table B1 Robustness Checks I

	Log Lactation Period (1)	Log Mean Yield (2)	Log Peak Yield (3)	Yield Curvature (4)	Log Mean SCC (5)	Log Trough SCC (6)	SCC Curvature (7)
Panel A: Baseline							
Ozone during pregnancy	-0.02432**	-0.05169***	-0.05128***	0.00398***	0.14676**	0.16330***	0.00585*
	(0.01165)	(0.01046)	(0.01148)	(0.00077)	(0.06727)	(0.04154)	(0.00343)
Ozone during lactation	0.00190	-0.00926	-0.02199**	0.00054	-0.08794*	0.02856	-0.00032
	(0.00923)	(0.00819)	(0.00905)	(0.00062)	(0.05301)	(0.03288)	(0.00273)
Observations	811,247	811,247	811,247	811,247	811,247	811,247	811,247
KP F-Statistics	2722	2722	2722	2722	2722	2722	2722
Panel B: Additional weather conditions (wind direction, precipitation)							
Ozone during pregnancy	-0.02426**	-0.05164***	-0.05121***	0.00398***	0.14703**	0.16330***	0.00586*
	(0.01165)	(0.01046)	(0.01148)	(0.00077)	(0.06727)	(0.04155)	(0.00343)
Ozone during lactation	0.00186	-0.00924	-0.02199**	0.00054	-0.08800*	0.02860	-0.00032
	(0.00923)	(0.00819)	(0.00904)	(0.00062)	(0.05301)	(0.03288)	(0.00273)
Observations	811,247	811,247	811,247	811,247	811,247	811,247	811,247
KP F-Statistics	2722	2722	2722	2722	2722	2722	2722
Panel C: Additional air pollutants (PM_{10}, SO_2, NO_2, CO)							
Ozone during pregnancy	-0.02433**	-0.05183***	-0.05152***	0.00399***	0.14641**	0.16284***	0.00584*
	(0.01165)	(0.01046)	(0.01148)	(0.00077)	(0.06728)	(0.04155)	(0.00343)
Ozone during lactation	0.00176	-0.00931	-0.02205**	0.00054	-0.08809*	0.02882	-0.00030
	(0.00923)	(0.00819)	(0.00904)	(0.00062)	(0.05301)	(0.03288)	(0.00273)
Observations	811,219	811,219	811,219	811,219	811,219	811,219	811,219
KP F-Statistics	2723	2723	2723	2723	2723	2723	2723
Panel D: Alternative FE (ID, ZIP-Month, Year-Month)							
Ozone during pregnancy	-0.02269*	-0.05298***	-0.05002***	0.00310***	0.12882*	0.16572***	0.00457
	(0.01185)	(0.01068)	(0.01172)	(0.00071)	(0.06967)	(0.04295)	(0.00354)
Ozone during lactation	0.00525	-0.01037	-0.02316***	-0.00036	-0.08181	0.02775	-0.00096
	(0.00902)	(0.00808)	(0.00894)	(0.00057)	(0.05306)	(0.03269)	(0.00274)
Observations	811,247	811,247	811,247	811,247	811,247	811,247	811,247
KP F-Statistics	2596	2596	2596	2596	2596	2596	2596
Panel E: Alternative Clustering Level (ZIP-Year, Individual)							
Ozone during pregnancy	-0.02432**	-0.05169***	-0.05128***	0.00398***	0.14676**	0.16330***	0.00585*
	(0.01165)	(0.01046)	(0.01148)	(0.00077)	(0.06727)	(0.04154)	(0.00343)
Ozone during lactation	0.00190	-0.00926	-0.02199**	0.00054	-0.08794*	0.02856	-0.00032
	(0.00923)	(0.00819)	(0.00905)	(0.00062)	(0.05301)	(0.03288)	(0.00273)
Observations	811,247	811,247	811,247	811,247	811,247	811,247	811,247
KP F-Statistics	2722	2722	2722	2722	2722	2722	2722

Notes: Panel A reports the baseline results. Panel B further controls for wind direction and precipitation. Panel C further controls for PM_{10}, SO_2, NO_2, and CO. Panel D includes alternative fixed effects. Panel E clusters the standard errors at the ZIP-by-year and individual levels (*** p<0.01, ** p<0.05, * p<0.1).

Table B2 Robustness Checks II

	Log Lactation Period (1)	Log Mean Yield (2)	Log Peak Yield (3)	Yield Curvature (4)	Log Mean SCC (5)	Log Trough SCC (6)	SCC Curvature (7)
Panel F: Alternative IV construction (taking account of wind speed)							
Ozone during pregnancy	-0.02386**	-0.05231***	-0.05198***	0.00391***	0.14239**	0.16021***	0.00573*
	(0.01144)	(0.01026)	(0.01127)	(0.00075)	(0.06598)	(0.04076)	(0.00336)
Ozone during lactation	0.00196	-0.00835	-0.01998**	0.00057	-0.08013	0.03090	-0.00024
	(0.00910)	(0.00808)	(0.00892)	(0.00061)	(0.05221)	(0.03240)	(0.00269)
Observations	811,247	811,247	811,247	811,247	811,247	811,247	811,247
KP F-Statistics	2772	2772	2772	2772	2772	2772	2772
Panel G: Alternative IV construction (specifying the ozone transmission time as 6 days)							
Ozone during pregnancy	-0.02420**	-0.05213***	-0.05193***	0.00395***	0.14741**	0.16266***	0.00589*
	(0.01163)	(0.01044)	(0.01146)	(0.00077)	(0.06714)	(0.04146)	(0.00342)
Ozone during lactation	0.00199	-0.00898	-0.02150**	0.00052	-0.08708*	0.02938	-0.00037
	(0.00921)	(0.00817)	(0.00903)	(0.00062)	(0.05285)	(0.03280)	(0.00272)
Observations	811,247	811,247	811,247	811,247	811,247	811,247	811,247
KP F-Statistics	2731	2731	2731	2731	2731	2731	2731
Panel H: Alternative IV construction (specifying the ozone transmission time as 8 days)							
Ozone during pregnancy	-0.02454**	-0.05148***	-0.05085***	0.00402***	0.14662**	0.16414***	0.00583*
	(0.01169)	(0.01049)	(0.01151)	(0.00077)	(0.06747)	(0.04168)	(0.00344)
Ozone during lactation	0.00217	-0.00922	-0.02220**	0.00055	-0.08891*	0.02769	-0.00028
	(0.00926)	(0.00822)	(0.00908)	(0.00062)	(0.05323)	(0.03300)	(0.00274)
Observations	811,247	811,247	811,247	811,247	811,247	811,247	811,247
KP F-Statistics	2712	2712	2712	2712	2712	2712	2712
Panel I: Alternative IV construction (specifying the upwind angle as smaller than 45 degrees)							
Ozone during pregnancy	-0.02481**	-0.06060***	-0.05338***	0.00451***	0.14764**	0.15757***	0.00552
	(0.01163)	(0.01043)	(0.01148)	(0.00077)	(0.06720)	(0.04138)	(0.00343)
Ozone during lactation	-0.00493	-0.01265	-0.02903***	0.00074	-0.12451**	0.01780	-0.00032
	(0.00928)	(0.00822)	(0.00907)	(0.00062)	(0.05322)	(0.03300)	(0.00274)
Observations	811,247	811,247	811,247	811,247	811,247	811,247	811,247
KP F-Statistics	2765	2765	2765	2765	2765	2765	2765
Panel J: Alternative IV construction (specifying the upwind angle as smaller than 60 degrees)							
Ozone during pregnancy	-0.02738**	-0.06039***	-0.05320***	0.00453***	0.16693**	0.17186***	0.00608*
	(0.01164)	(0.01044)	(0.01147)	(0.00077)	(0.06732)	(0.04143)	(0.00343)
Ozone during lactation	-0.00294	-0.00910	-0.02496***	0.00074	-0.10813**	0.02148	-0.00005
	(0.00921)	(0.00817)	(0.00902)	(0.00061)	(0.05293)	(0.03281)	(0.00272)
Observations	811,247	811,247	811,247	811,247	811,247	811,247	811,247
KP F-Statistics	2787	2787	2787	2787	2787	2787	2787

Notes: This table reports results based on IVs constructed differently from the baseline estimation. Panel F takes account of wind speed when constructing the IV. Panels G and H specify the ozone transmission time as 6 days and 8 days, respectively. Panels I and J specify the upwind angle as smaller than 45 degrees and 60 degrees, respectively (*** p<0.01, ** p<0.05, * p<0.1).

Table B3 Robustness Checks III

	Log Lactation Period (1)	Log Mean Yield (2)	Log Peak Yield (3)	Yield Curvature (4)	Log Mean SCC (5)	Log Trough SCC (6)	SCC Curvature (7)
Panel K: M7							
M7 during Pregnancy	-0.02384**	-0.05009***	-0.04913***	0.00386***	0.14721**	0.15827***	0.00573*
	(0.01145)	(0.01028)	(0.01129)	(0.00075)	(0.06621)	(0.04087)	(0.00337)
M7 during Lactation	0.00114	-0.01070	-0.02324***	0.00065	-0.08226	0.03312	-0.00014
	(0.00906)	(0.00804)	(0.00889)	(0.00061)	(0.05193)	(0.03224)	(0.00268)
Observations	811,247	811,247	811,247	811,247	811,247	811,247	811,247
KP F-Statistics	2251	2251	2251	2251	2251	2251	2251
Panel L: M12							
M12 during Pregnancy	-0.02489**	-0.05174***	-0.05021***	0.00400***	0.15685**	0.16352***	0.00598*
	(0.01199)	(0.01076)	(0.01182)	(0.00078)	(0.06944)	(0.04284)	(0.00353)
M12 during Lactation	0.00161	-0.01002	-0.02287**	0.00060	-0.08690	0.03096	-0.00025
	(0.00930)	(0.00826)	(0.00913)	(0.00063)	(0.05338)	(0.03313)	(0.00275)
Observations	811,247	811,247	811,247	811,247	811,247	811,247	811,247
KP F-Statistics	2082	2082	2082	2082	2082	2082	2082
Panel M: AOT40							
AOT40 during Pregnancy	-0.01469**	-0.03248***	-0.03345***	0.00248***	0.08134**	0.10256***	0.00355*
	(0.00705)	(0.00634)	(0.00696)	(0.00047)	(0.04046)	(0.02506)	(0.00207)
AOT40 during Lactation	0.05210	0.05188	-0.00516	-0.00476	-0.65254**	-0.16698	-0.01193
	(0.04854)	(0.04300)	(0.04743)	(0.00306)	(0.28386)	(0.17465)	(0.01434)
Observations	811,247	811,247	811,247	811,247	811,247	811,247	811,247
KP F-Statistics	2399	2399	2399	2399	2399	2399	2399
Panel N: W126							
W126 during Pregnancy	-0.02116**	-0.04737***	-0.04931***	0.00361***	0.11385*	0.14953***	0.00512*
	(0.01019)	(0.00917)	(0.01007)	(0.00069)	(0.05838)	(0.03618)	(0.00300)
W126 during Lactation	0.04596	0.00081	-0.09243	-0.00133	-0.83407**	-0.00760	-0.01006
	(0.07112)	(0.06299)	(0.06956)	(0.00462)	(0.41256)	(0.25474)	(0.02103)
Observations	811,247	811,247	811,247	811,247	811,247	811,247	811,247
KP F-Statistics	2742	2742	2742	2742	2742	2742	2742

Notes: This table reports results based on different ozone metrics. Weather controls include the quadratic polynomials of THI, wind speed, surface pressure, and solar radiation. Standard errors are two-way clustered at the cow and county-by-year levels (*** p<0.01, ** p<0.05, * p<0.1).