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Short-term effects of air pollution and temperature on cattle mortality in the Netherlands

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ABSTRACT

Background: Extreme temperatures and air pollution are both associated with increased mortality risk in humans. However, the effects of temperature and air pollution on cattle have not been investigated much before.
Objectives: Short-term effects of temperature (heat and cold) and air pollution on cattle mortality were investigated and quantified in the Netherlands during 2012–2017.
Methods: Daily data on cattle mortality, weather conditions and mean levels of particulate matter (PM_{10}), ozone (O_3), ammonia (NH_3) and nitrogen dioxide (NO_2) of the Netherlands during 2012–2017 were collected. Associations were investigated with time–series regression using distributed lag non–linear models including lags of up to 25 days. Effects of temperature were expressed as those associated with extreme and moderate heat or cold, defined as Temperature Humidity Index (THI) values below the 1st and 5th percentile, and above the 95th and 99th percentile of the national THI distribution. Effects of air pollutants were expressed per 10 μg/m^3 change in daily mean concentrations.
Results: Both high and low temperatures were associated with increased mortality amongst different age groups. For instance, the newborn calves of at most 14 days showed a cumulative relative risk (RR) of 2.13 (95%CI: 1.99–2.28) for extreme heat and the pre-weaned calves (15–55 days) showed a cumulative RR of 1.50 (95%CI: 1.37–1.64) for extreme cold. Associations of air pollution with mortality were not consistent, except for the effect of ozone of lag 0–7 and lag 0–25. Exposure to O_3 in the newborn calves resulted in a cumulative RR of 1.09 (95%CI: 1.04–1.4) for lag 0–7 and 1.09 (95%CI: 1.03–1.16) for lag 0–25.
Conclusions: Both high and low temperatures were associated with increased mortality amongst pre-weaned calves of 15–55 days, whereas associations in weaned calves (56 days – 1 year) were only observed for low temperatures and in newborn calves of at most 14 days and lactating cattle > 2 years only for high temperatures. Associations of air pollution with mortality in all age groups were not consistent, except for the effect of ozone of lag 0–7 and lag 0–25.

1. Introduction

Short-term variations in temperature and air pollution are well known determinants of short-term variations in human mortality. In comparison, few studies have looked at associations between temperature and mortality among cattle (Bishop-Williams et al., 2015; Cox et al., 2016a; Crescio et al., 2010; Morignat et al., 2017, 2015; Stull et al., 2008; Vitali et al., 2015), and only one study focused on associations between air pollution and cattle mortality (Cox et al., 2016b). High temperatures were more commonly found to be associated with increased cattle mortality than with low temperatures. In humans, low temperatures were more associated with increased mortality (Gasparrini et al., 2015; Huang et al., 2015). When this excess mortality is followed by a temporary decrease in deaths, this short-term shift is called the harvesting effect (Cox et al., 2016a).

The ambient temperature influences cow health and production, including growth, reproduction and lactation (Collier et al., 2006). The effect of temperature depends on the thermoneutral zone (TNZ) of cows. Within this ambient temperature range, cows are able to keep their body core temperature stable by only regulating their heat loss (IUPS Thermal Commission, 2001). Important is that the TNZ differs per species, for humans the range is 24–31 °C and for dairy cattle it

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ranges from 5 to about 16 °C (Gordon, 2005; Hahn, 1999). For calves the TNZ range differs with their age. For newborn calves, it ranges from 18 to 25 °C and for calves up to 1 month from 13 to 25 °C (Hahn, 1999). While Schrama (1993) found a lower critical temperature of 12.5 °C for newborn calves.

The effects of exposure to particulate matter, nitrogen dioxide and ozone on cattle mortality were only investigated by one Belgian study (Cox et al., 2016b) with mixed results, e.g. only for ozone significant associations were found that persisted over a period of 25 days. The following constituents were investigated: particulate matter (PM_{10}), nitrogen dioxide (NO_2), ammonia (NH_3) and ozone (O_3). Within the present study, the effect of daily variations in air pollution levels and ambient air temperature on cattle mortality were investigated between July 2012 and June 2017 in the Netherlands. The objective of this study was to provide a quantitative insight in the number of cattle deaths that are associated with short-term variations in temperature and air pollution.

2. Materials and methods

2.1. Data sources

Daily data on cattle mortality (including unplanned farm deaths or euthanasia) were obtained from the identification and registration (I&R) data of the Netherlands Enterprise Agency (RVO). This data included both dairy and beef cattle from all ages between July 2012 and June 2017. Veal calves were excluded from this study as they are permanently housed unlike the other herd types. The majority of dairy cattle spend most of their time outside during summer (grazing season) but are indoors in winter. Beef cattle spend most of their time outside. Cattle are housed in fairly open stables with often natural ventilation. Calves and cows (all types) were divided in the following five age groups: newborn calves of at most 14 days, pre-weaned calves of 15–55 days, weaned calves of 56 days–1 year, young stock of 1–2 years and lactating cows older than 2 years. Age groups were based on differences in mortality rates, management and physiology, e.g. lactating vs. non-lactating and individual housing vs. group housing (Santman-Berends et al., *in press*). We obtained information on the national number of live animals, number of deaths and two-digit postal code on each day in our study period.

Data on daily relative humidity levels and daily air temperatures were obtained from the Royal Dutch Meteorology Institute (KNMI, 2018). We used data from 36 regional weather stations from all provinces. And the average daily temperature (T) and relative humidity (RH) were obtained from hourly data of these stations. As the Netherlands is small (41,526 km^2), with little climatic variation and small elevation differences, data of different weather stations from all Dutch provinces were combined into a mean daily value of minimum, average and maximum temperature and relative humidity (Hoek et al., 2000).

Daily air pollution levels (μg/m^3) of particulate matter with a diameter smaller than 10 μm (PM_{10}), ozone (O_3), ammonia (NH_3) and nitrogen dioxide (NO_2) were obtained from the National Institute for Public Health and the Environment (RIVM, 2018). We obtained data from 32 measuring stations across the country. Then we combined the average daily levels of the different measuring stations into a country-specific daily average level of each constituent.

2.2. Statistical analysis

To describe the effect of ambient weather conditions on cattle mortality, data on T as well as RH were also included, because RH influences the heat transfer possibilities. Therefore, the temperature humidity index (THI) was used. Therefore, the THI from Crescio et al. (2010) was used for Eq. (1).

$$THI\ (°C) = T_{air} - 0.55 \times (1 - 0.01RH) \times (T_{air} - 14.5) \quad (1)$$

with T_{air} (air temperature) in °C and RH (relative humidity) as percentage

Statistical analyses were done using the statistical software R and the 'dlnm' package (Gasparrini, 2011; R Studio Team, 2016). With this package, distributed lag non–linear models (DLNM) with a 'cross–basis' function for daily mean THI and for daily mean level of each air pollutant were fitted to investigate the associations between daily cattle mortality and THI and air pollution (PM_{10}, NO_2, O_3 and NH_3). Quasi–Poisson models were used to allow overdispersion in daily cow deaths. Each age group had its own model. Modelling choices were based on similar studies in Belgium and France (Cox et al., 2016a, 2016b; Morignat et al., 2017), which models included variables of the lag–response and exposure–response association.

2.3. Lag–response association

As described by Cox et al. (2016a) and Morignat et al. (2017), a natural cubic spline, with 5 ° of freedom (df), was used to model the lag–response association for both THI and air pollution. The maximum lag was set at 25 days, to see if there is a harvesting effect and to catch delayed effects. Harvesting would result in a temporary decrease in the expected number of deaths after a period with excess mortality (Qiao et al., 2015). To address this issue, the lag was set up to 25 days, which was based on previous studies (Cox et al., 2016a; Cox et al., 2016b). Because, when the excess mortality risk lasted over this period of 25 days after exposure, the impact of for example heat was considered relevant for animal health. Lag knots were set at equally spaced values on the logarithmic scale of the lag, in order to allow more flexibility (Cox et al., 2016a; Gasparrini, 2011).

2.4. Exposure–response association

To model the THI–cattle mortality association, a natural cubic spline, with 4 df, was chosen (Cox et al., 2016a; Morignat et al., 2017). To correct for seasonal and/or long–term trends, a smooth function of the time, with 4 df per year, a factor 'day of the week' and a factor 'public holiday' were added (Gasparrini et al., 2015; Morignat et al., 2017). Also, the log of the number of cattle at risk on the day was included as an offset variable (Morignat et al., 2017). The 1 st, 5th, 95th and 99th percentiles of the national–level THI distribution were used to indicate the cut–off points of extreme cold, moderate cold, moderate heat and extreme heat. For each age group, a minimum mortality temperature humidity index (MMTHI) was calculated and used as reference to calculate the relative risk (RR) for extreme cold, moderate cold, moderate heat and extreme heat. The MMTHI was defined using the method described by Vicedo-Cabrera et al. (2016) and Gasparrini et al. (2015b): scanning through the prediction to find the THI that minimizes the mortality. It can be difficult to identify one point as the lowest (for example, in J- or U-shaped curves), the 95% confidence intervals (CIs) of the MMTHI was estimated according to Tobías et al. (2017). They designed an algorithm to estimate the CI and standard error for the MMT from a temperature-mortality shape estimated with splines. The TNZ was estimated by screening the lower limit of the CI of the overall cumulative RR. When the lower limit of the cumulative overall RR was > 1.00, this value was used as lower or upper critical temperature of the TNZ.

To model the effect of air pollution on cattle mortality, single–-pollutant models were used for PM_{10}, NO_2, O_3 and NH_3. A linear relationship between each air pollutant and mortality was assumed. Associations between air pollution and mortality were always adjusted for THI. Cox et al. (2016b) described different effects of air pollution on dairy cattle mortality during winter and summer. Therefore, we investigated the associations during the whole period and performed a subgroup analysis with the warm (grazing) season (April–September) and the cold (housing) season (October–March). The RR's of cattle mortality were calculated per 10 μg/m^3 increase of each constituent during the whole period, and during the warm and cold seasons. In addition to the total lag period of 0–25 days, possible acute effects of air pollution were estimated by adding the following lag periods: lag 0, lag 0–1 and lag 0–7. The advantage of a distributed lag model is that it provides cumulative effects of the exposure by flexibly estimating contributions at different lag times (Cox et al., 2016b). In the second stage of analysis, a two-pollutant model with NO_2 and O_3 was constructed because those pollutants were negatively correlated to each other. Other pollutants were not used in the two-pollutant model, because no consistent outcomes were found for PM_{10} and NH_3. For the air pollution- and THI-cattle mortality association, the model fit of each age group was investigated by plotting the deviance residuals over time. This deviance can be interpreted as measure of goodness of the model fit; it shows the difference between the actual model fit and the model fit of an ideal model.

2.5. Sensitivity analysis

The modelling parameters were based on similar studies. Sensitivity analyses on different modelling choices for these modelling parameters were performed for both the models of THI and air pollution. The modelling parameters for the model of temperature and cattle mortality were: maximum lag period of 14 days, 3 df and 5 df used for seasonal control and long-term trends, 3 df and 5 df for the THI-mortality association, 4 df and 6 df for the lag-response association and adding a parameter for NO_2, O_3, PM_{10} and NH_3 individually. The modelling parameters for the model of air pollution and cattle mortality were: maximum lag period of 14 days, 3 df and 5 df used for seasonal control and long–term trends, 3 df and 5 df for the THI–mortality association and 4 df and 6 df for the lag–response association. We also used an unconstrained distributed lag model for the sensitivity analyses of air pollution, within this model each lag is entered as a separate variable (Cox et al., 2016b).

3. Results

The results from the sensitivity analysis and the random pattern of deviance residual plots indicate that the models fit the data well. Only a few outliers in this 5-year period were observations with a deviance residual above two. Table 1 provides descriptive statistics on mean levels of air pollution and weather.

Pearson correlation coefficients of THI, RH and air pollutants are provided in Table 2. Overall, the correlation between NO_2 and PM_{10} was high, while O_3 and NO_2 had a strong negative correlation. During the warm (grazing) season, the THI was positively correlated with most air pollutants. During the cold (housing) season, the THI was negatively correlated with NO_2 and with PM_{10}, and positively correlated with O_3.

3.1. Estimation of the THI–cattle mortality association

The cut–off points (1st, 5th, 95th and 99th percentiles) of the THI distribution were: -0.8 °C_{THI} for extreme cold, 1.9 °C_{THI} for moderate cold, 19.2 °C_{THI} for moderate heat and 21.6 °C_{THI} for extreme heat. The data-driven MMTHI was estimated for all age categories: 9.7 °C_{THI} for newborn calves, 11 °C_{THI} for pre-weaned calves, 17.3 °C_{THI} for weaned calves, -4.6 °C_{THI} for young stock and 4.8 °C_{THI} for lactating cattle. In Fig. 1, the estimated MMTHI including the 95% confidence intervals, are shown for each age group. The confidence intervals become wider, when the shape of the THI-mortality curve included a temperature range (plateau) with a RR not different from 1.00. As is evident from the figure, all intervals overlap.

The estimated statistical thermoneutral zone (TNZ) for newborn calves was -4.6–1.6 °C_{THI}, for pre-weaned calves it was 9.3–13.9 °C_{THI}, for weaned calves 3.1–23.7 °C_{THI}, for young stock -4.6–22.5 °C_{THI} and for cows > 2 years it was -4.6–16.8 °C_{THI}. In Table 3, the RRs for extreme and moderate cold and heat are shown. The newborn calves were most susceptible to heat. The pre-weaned calves were susceptible for both heat and cold. And weaned calves were only sensitive to moderate and extreme cold. For young stock no significant results were found. And lactating cows were sensitive to moderate and extreme heat.

In Fig. 2, the overall cumulative THI-cattle mortality association is shown for all age groups. The histogram on the secondary y-axis shows the total deaths for each THI degree; the larger numbers of death in the centre part of the distribution simply reflects that here are more days with moderate than with extremely high or low temperatures. The non-linear relationship between THI and cattle mortality was J-shaped for newborn calves and lactating cows. These curves were reverse J-shaped for pre-weaned calves and weaned calves.

Table 1
Summary statistics for daily temperature, RH, THI and air pollutants 2012–2017, the Netherlands.

Variable	Mean	Median	SD	Min	Max
Temperature (°C)	10.5	10.2	6.0	−5.9	26.3
Relative humidity (%)	81.7	82.7	8.2	38.9	98.1
THI (°C_{THI})	10.8	10.6	5.4	−4.6	23.7
NH_3 (μg/m^3)	12.5	10.9	7.9	1.6	66.3
NO_2 (μg/m^3)	18.5	16.8	8.2	4.6	52.8
O_3 (μg/m^3)	45.3	46.9	18.8	1.2	113.4
PM_{10} (μg/m^3)	18.3	15.9	9.1	5.8	85.8

Table 2
Matrix of Pearson's correlation coefficients of THI and air pollutants between 2012–2017 in the Netherlands. When values are shown in bold, a P-value < 0.01 was found.

Whole year	THI (°C_{THI})	PM_{10} (μg/m^3)	NH_3 (μg/m^3)	NO_2 (μg/m^3)	O_3 (μg/m^3)
THI (°C_{THI})	–				
PM_{10} (μg/m^3)	**−0.25**	–			
NH_3 (μg/m^3)	**0.30**	**0.37**	–		
NO_2 (μg/m^3)	**−0.46**	**0.56**	**0.16**	–	
O_3 (μg/m^3)	**0.45**	**−0.31**	**0.09**	**−0.68**	–
Warm season	THI (°C_{THI})	PM_{10} (μg/m^3)	NH_3 (μg/m^3)	NO_2 (μg/m^3)	O_3 (μg/m^3)
THI (°C_{THI})	–				
PM_{10} (μg/m^3)	**0.17**	–			
NH_3 (μg/m^3)	**0.39**	**0.48**	–		
NO_2 (μg/m^3)	0.07	**0.61**	**0.44**	–	
O_3 (μg/m^3)	0.06	**0.15**	**0.17**	**−0.17**	–
Cold season	THI (°C_{THI})	PM_{10} (μg/m^3)	NH_3 (μg/m^3)	NO_2 (μg/m^3)	O_3 (μg/m^3)
THI (°C_{THI})	–				
PM_{10} (μg/m^3)	**−0.34**	–			
NH_3 (μg/m^3)	−0.01	**0.43**	–		
NO_2 (μg/m^3)	**−0.37**	**0.51**	**0.29**	–	
O_3 (μg/m^3)	**0.15**	**−0.43**	**−0.23**	**−0.77**	–

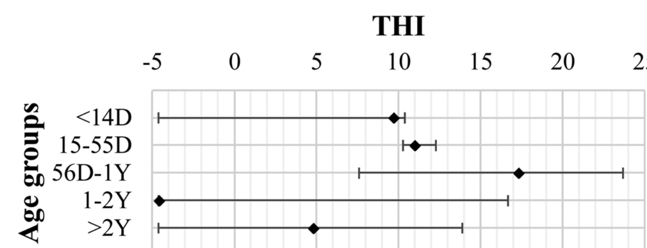

Fig. 1. Forest plot for the estimated data-driven MMTHI (minimum mortality temperature) with 95% confidence intervals, for all age groups of cattle in the Netherlands between 2012 and 2017. Age groups include: < 14 days, 15–55 days, 56 days – 1 year, 1–2 years, and > 2 years.

Table 3
Association of heat and cold spells on cattle mortality (expressed as temperature humidity index - THI) for all age groups of cattle in the Netherlands between 2012 and 2017. Cut-off temperatures were used to define extreme and moderate heat and extreme and moderate cold. Significant associations are shown in bold.

	Extreme cold	Moderate cold	Moderate heat	Extreme heat
Cut-off temperatures	$-0.8\ ^{\circ}C_{THI}$	$1.9\ ^{\circ}C_{THI}$	$19.2\ ^{\circ}C_{THI}$	$21.6\ ^{\circ}C_{THI}$
Newborn calves 95% CI	1.04 (0.98–1.12)	1.05 (1.00–1.10)	**1.70 (1.61–1.80)**	**2.13 (1.99–2.28)**
Pre-weaned calves 95% CI	**1.50 (1.37–1.64)**	**1.36 (1.27–1.46)**	**1.18 (1.10–1.27)**	**1.21 (1.09–1.34)**
Weaned calves 95% CI	**1.17 (1.02–1.35)**	**1.14 (1.01–1.27)**	1.00 (0.97–1.04)	1.01 (0.92–1.11)
Young stock 95% CI	1.12 (0.96–1.30)	1.20 (0.95–1.51)	1.27 (0.93–1.74)	1.34 (0.98–1.84)
Lactating cattle 95% CI	1.01 (0.93–1.09)	1.00 (0.97–1.04)	**1.17 (1.08–1.28)**	**1.27 (1.14–1.41)**

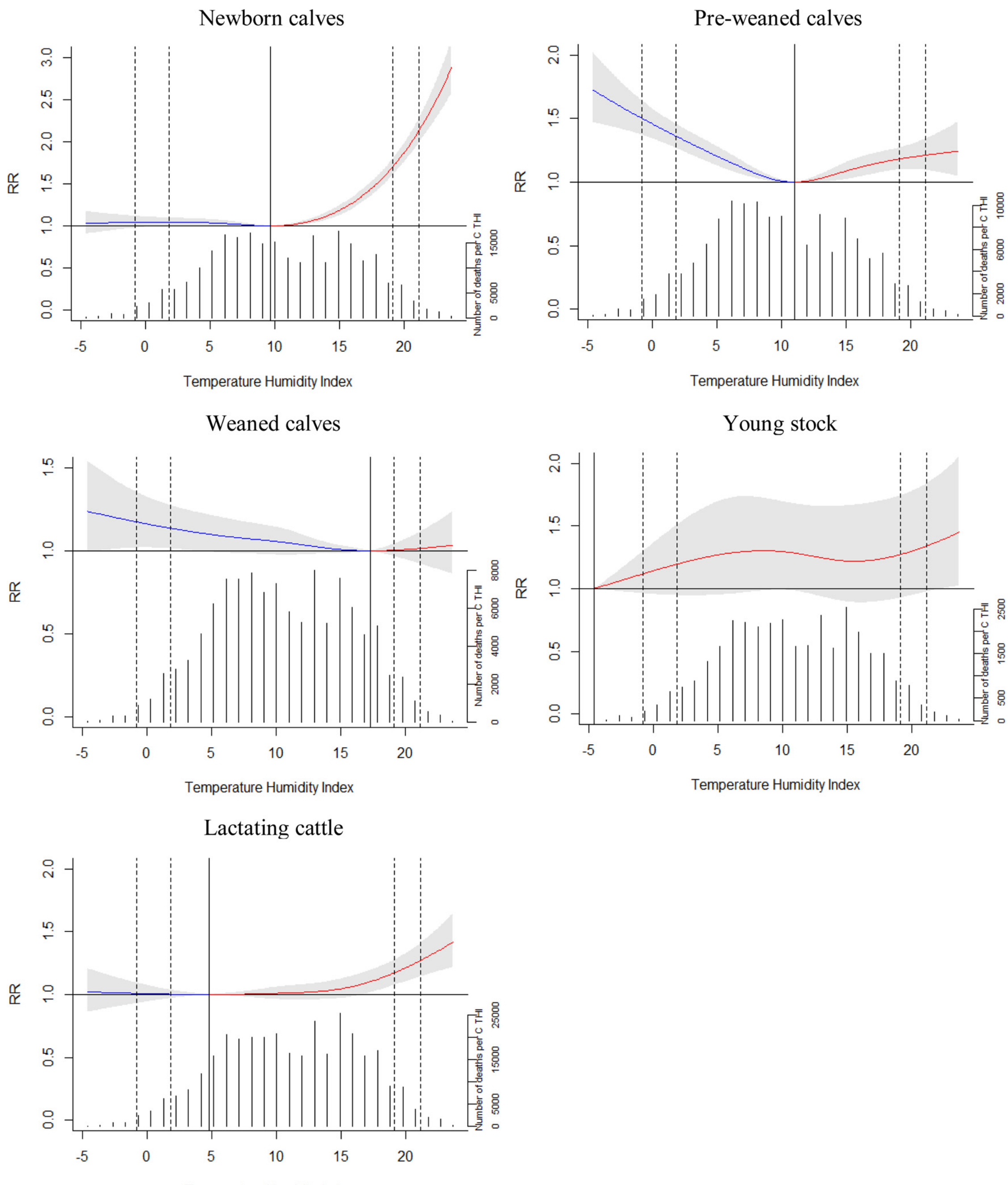

Fig. 2. Overall cumulative temperature humidity index (THI)-mortality association for calves and cows, with 95% CI as the shaded grey area. The solid vertical line represents the minimum mortality temperature (MMTHI) and the dashed vertical lines represent the 1st, 5th, 95th and 99th percentiles of the national-level THI distribution. The secondary y-axis (and associated histogram) shows the total deaths at each THI (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 4
Effects of NO_2, O_3, PM_{10} and NH_3 on cattle mortality in single pollutant models expressed as relative risk (RR) for different lag periods. The RRs indicate the change in cattle mortality for a 10 μg/m^3 increase above mean national–level of these constituents. RR with significant associations are shown in bold.

	Newborn calves RR (95% CI)	Pre-weaned calves RR (95% CI)	Weaned calves RR (95% CI)	Young stock RR (95% CI)	Lactating cattle RR (95% CI)
NO_2 single pollutant model					
Lag 0	1.04 (1.00–1.08)	1.03 (0.98–1.09)	1.04 (0.98–1.10)	1.09 (1.00–1.17)	1.04 (0.99–1.08)
Lag 0–1	1.03 (0.99–1.07)	1.03 (0.97–1.08)	1.05 (1.00–1.12)	1.08 (1.00–1.17)	1.02(0.97–1.07)
Lag 0–7	0.92 (0.88–0.97)	0.89 (0.84–0.94)	0.93 (0.87–0.99)	1.00 (0.92–1.10)	0.90(0.85–0.95)
Lag 0–25	0.89 (0.82–0.95)	0.79 (0.72–0.88)	0.90 (0.81–1.00)	0.99 (0.85–1.15)	0.84 (0.77–0.91)
O_3 single pollutant model					
Lag 0	1.00 (0.96–1.03)	0.97 (0.92–1.03)	1.00 (0.94–1.06)	0.95 (0.88–1.03)	1.01 (0.97–1.06)
Lag 0–1	0.99 (0.95–1.03)	0.96 (0.91–1.02)	0.98 (0.93–1.04)	0.95 (0.87–1.04)	1.01 (0.97–1.06)
Lag 0–7	**1.09 (1.04–1.14)**	**1.08 (1.02–1.14)**	**1.11 (1.04–1.18)**	1.02 (0.93–1.10)	**1.07 (1.02–1.12)**
Lag 0–25	**1.09 (1.03–1.16)**	**1.12 (1.03–1.22)**	**1.16 (1.06–1.27)**	1.10 (0.97–1.25)	**1.11 (1.04–1.20)**
PM_{10} single pollutant model					
Lag 0	1.01 (0.98–1.04)	1.00 (0.96–1.04)	0.99 (0.95–1.04)	0.99 (0.93–1.05)	0.98 (0.95–1.02)
Lag 0–1	1.01 (0.98–1.04)	1.01 (0.97–1.05)	1.00 (0.95–1.04)	0.98 (0.92–1.04)	0.98 (0.94–1.01)
Lag 0–7	0.97 (0.94–1.00)	0.98 (0.94–1.02)	0.96 (0.92–1.01)	0.95 (0.89–1.02)	0.94 (0.90–0.97)
Lag 0–25	0.89 (0.85–0.94)	0.92 (0.86–0.99)	0.94 (0.87–1.01)	0.89 (0.80–0.98)	0.88 (0.83–0.93)
NH_3 single pollutant model					
Lag 0	1.03 (1.00–1.06)	1.04 (0.99–1.09)	1.03 (0.98–1.08)	**1.08 (1.01–1.15)**	1.02 (0.99–1.06)
Lag 0–1	1.02 (0.99–1.05)	1.03 (0.99–1.08)	1.03 (0.98–1.08)	1.06 (1.00–1.13)	1.01 (0.97–1.04)
Lag 0–7	0.98 (0.95–1.01)	0.96 (0.92–1.00)	0.99 (0.94–1.03)	1.00 (0.94–1.06)	0.94 (0.91–0.97)
Lag 0–25	0.94 (0.90–0.98)	0.91 (0.85–0.97)	0.98 (0.91–1.05)	0.95 (0.87–1.04)	0.92 (0.87–0.97)

3.2. Estimation of the air pollution–cattle mortality association

Overall, the significant correlation between NO_2 and PM_{10} was high, while O_3 and NO_2 had a significant, strong negative correlation. Effects of PM_{10}, NO_2, O_3 and NH_3 on cattle mortality were estimated. In addition to the overall cumulative RR of the lag 0–25 period, possible acute effects of air pollution were estimated as lag 0, lag 0–1 and lag 0–7 cumulative RR's for each age group. In Table 4, the effects of a 10 μg/m^3 increase of NO_2, O_3, PM_{10} and NH_3 on cattle mortality are given. For exposure to NO_2, an acute effect at lag 0 was seen for all age groups, although not significant. And for exposure to ozone, a delayed effect was seen at lag 0–7 and at lag 0–25 for the pre-weaned and weaned calves and lactating cattle. For PM_{10} and NH_3 almost no effects were seen. When a two–pollutant model with NO_2 and O_3 was used, the effects on cattle mortality stayed more or less the same for both NO_2 and for O_3. These results are shown in Table 5. For lactating cattle, the acute effect of NO_2 even became significant with the two-pollutant model.

In short, the following significant effects were seen during the warm season. An exposure to NO_2 resulted for newborn calves in a RR of 1.20 (95%CI:1.06–1.37) for lag 0–25, for pre-weaned calves in a RR of 1.24 (95%CI:1.03–1.50) for lag 0–25. For O_3 no significant results were found. For an increase in PM_{10}, newborn calves showed a RR of 1.08 (95%CI:1.02–1.15) for lag 0–1 and a RR of 1.11 (95%CI:1.04–1.19) for lag 0–7. For pre-weaned calves an increase in PM_{10} resulted in a RR of 1.10 (95%CI:1.01–1.19) for lag 0, a RR of 1.15 (95%CI:1.06–1.25) for lag 0–1 and in a RR of 1.15 (95%CI:1.05–1.26) for lag 0–7. An increase in NH_3 resulted in the age group of newborn calves in a RR of 1.08 (95%CI:1.03–1.14) for lag 0, in a RR of 1.08 (95%CI:1.03–1.14) for lag 0–1 and in a RR of 1.07 (95%CI:1.01–1.13) for lag 0–7. In the two-pollutant model with NO_2 and O_3, newborn calves showed a RR of 1.14 (95%CI:1.00–1.29) for NO_2 during lag 0–25, while pre-weaned calves showed a more acute effect: a RR of 1.14 (95%CI:1.02–1.28) for lag 0 and 1.17 (95%CI:1.03–1.32) for lag 0–1.

During the cold season, less effects of air pollution were seen. An increase in NO_2 resulted for newborn calves in a RR of 1.06 (95%CI:1.01–1.12) for lag 0. In young stock, a RR of 1.13 (95%CI:1.02–1.25) was found for lag 0 and a RR of 1.12 (95%CI: 1.01–1.25) for lag 0–1. An increase in O_3 resulted in lactating cattle in a RR of 1.08 (95%CI:1.02–1.15) for lag 0–25. In the two-pollutant model the effects of NO_2 and O_3 were not significant during the cold season.

The model fit was investigated by plotting the residuals of the THI-cattle mortality association. For all age groups the residuals were centred around zero, throughout the whole range of fitted values. When performing the sensitivity analyses for the air pollution- and THI–cattle mortality association, results were stable amongst all age groups. A deviation of 20% or smaller of the main model was considered as stable. Lag–specific RR's, calculated from single pollutant models, are shown for a 10 μg/m^3 increase above mean national–level for lactating cows in Fig. 3.

4. Discussion

The findings provide evidence of an increased risk of calf and cow

Table 5
Effects of NO_2 and O_3 on cattle mortality in two-pollutant models expressed as relative risk (RR), for different lag periods. The RRs indicate the change in cattle mortality for a 10 μg/m^3 increase above mean national–level of these constituents. RRs with significant associations are shown in bold.

	Newborn calves RR (95% CI)	Pre-weaned calves RR (95% CI)	Weaned calves RR (95% CI)	Young stock RR (95% CI)	Lactating cattle RR (95% CI)
NO_2 two-pollutant model					
Lag 0	**1.06 (1.01–1.12)**	1.03 (0.96–1.11)	1.07 (0.99–1.15)	1.08 (0.97–1.20)	**1.08 (1.02–1.15)**
Lag 0–1	1.03 (0.98–1.09)	1.00 (0.92–1.08)	1.06 (0.98–1.15)	1.06 (0.95–1.18)	1.04 (0.98–1.11)
Lag 0–7	0.96 (0.90–1.02)	0.87 (0.79–0.94)	0.97 (0.88–1.06)	0.99 (0.87–1.13)	0.89 (0.83–0.96)
Lag 0–25	0.92 (0.84–1.01)	0.77 (0.68–0.88)	1.01 (0.88–1.17)	1.09 (0.90–1.33)	0.85 (0.76–0.95)
O_3 two-pollutant model					
Lag 0	1.03 (0.98–1.09)	0.99 (0.92–1.07)	1.04 (0.97–1.13)	1.00 (0.90–1.11)	1.06 (1.00–1.12)
Lag 0–1	1.01 (0.96–1.07)	0.96 (0.89–1.03)	1.02 (0.94–1.10)	0.98 (0.88–1.09)	1.03 (0.97–1.10)
Lag 0–7	1.05 (1.00–1.12)	0.98 (0.90–1.06)	1.08 (1.00–1.18)	1.01 (0.90–1.18)	1.00 (0.94–1.07)
Lag 0–25	1.05 (0.97–1.13)	0.98 (0.88–1.10)	**1.17 (1.04–1.31)**	1.16 (0.99–1.37)	1.03 (0.94–1.13)

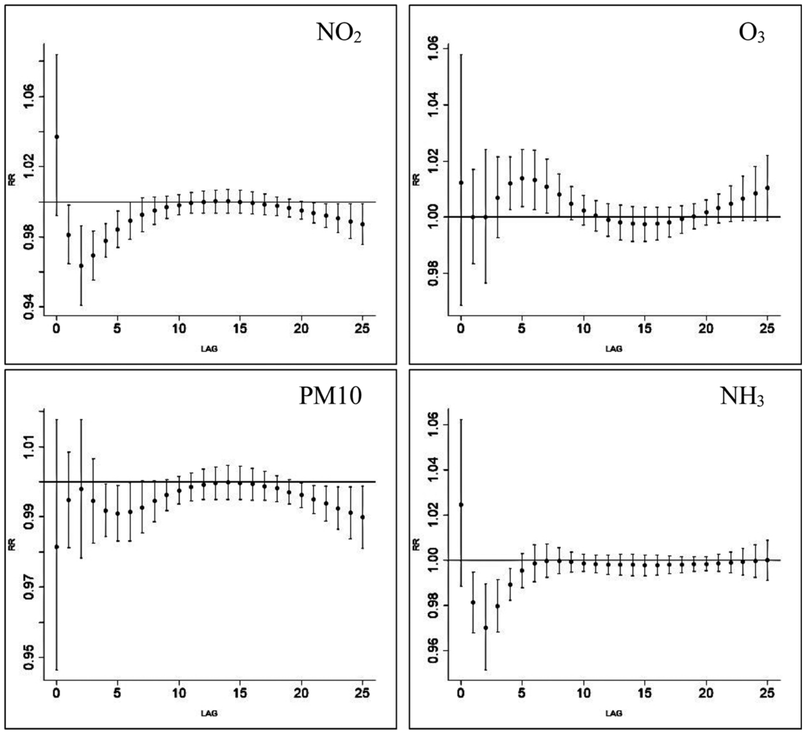

Fig. 3. Single pollutant model: lag–specific relative risks for a 10 μg/m^3 increase above mean national-level of NO_2, O_3, PM_{10} and NH_3 for lactating cows of 2 years and older in the Netherlands between 2012 and 2017. The error–bars represent 95% confidence intervals.

death from moderate and extreme cold and heat. Small effects of air pollution (mainly NO_2 and O_3) on cattle mortality were found. However, the air pollution effects were not consistent in all age groups. The model fitted the data well, given the results from the sensitivity analysis and the random pattern of deviance residual plots. In human mortality studies, the lag period differs between 21 days and 30 days (Gasparrini et al., 2015; Analitis et al., 2008). For cattle, the lag-period of 25 days seemed a bit long, given that no effects were seen for those long lag-times.

4.1. Temperature–cattle mortality association

Effect estimates for cows of 2 years and older were compared with similar studies in Belgium, France and Italy. For cold, a lower mortality risk was observed for adult dairy cattle compared to the studies in France and Belgium. And for heat, the results were in the same range as studies in Belgium and France. Only the mortality risk for heat in a study in Italy (Crescio et al., 2010), expressed as an odds ratio, is higher than for adult dairy cattle identified in this study. Morignat et al. (2017) already discussed that differences in study population (breed and age), farming practices (risk-mitigating measures for cold and heat, type of animal housing) and cut-off values for moderate and extreme heat can affect the outcome. This work suggests that study period (whole year or only summers) and study location, including differences in climatic zones, can explain differences in outcome for mortality risk as well. Temperature–mortality curves frequently do not show a clear minimum, meaning that the estimated MMT can be imprecise (Tobías et al., 2017). Therefore, we calculated the 95% CIs of the MMTHI and defined the data-driven, statistical thermoneutral zone as the interval in which the RR curves did not significantly deviate from 1.00.

4.2. Heat stress and mortality

Heat stress can have both direct (caused by hyperthermia) and indirect (caused by changes in feed intake and behaviour) health effects (Bernabucci et al., 2010). Heat-related health issues in cattle, caused by increased body core temperature with 3–4 °C, are: heat stroke, heat exhaustion, heat syncope, heat cramps and organ dysfunction (Bernabucci et al., 2010). Heat stress also reduces the intestinal blood flow which could cause a disruption in the intestinal barrier. This disruption can lead to increased intestinal permeability which could cause endotoxemia or even death within an animal (Lambert, 2009). Another heat-related problem in ruminants is the development of sub-clinical or clinical (secondary) ketosis due to a lower feed intake (Duffield, 2000). Rumen health is adversely affected by heat stress. The lower feed intake reduces the ruminating process which will result in a decreased level of buffering agents (from saliva) in the rumen. This decreased level of buffering agents in the rumen makes cattle more susceptible for subclinical and acute rumen acidosis (Kadzere et al., 2002). Acute rumen acidosis can lead to death by damage of the intestinal wall, decreased blood pH, dehydration and metabolic acidosis (Owens et al., 1998). An Australian study that investigated cattle deaths during sea transport found that apparent heat stroke was commonly found in cattle with pneumonia (Norris et al., 2003). Pneumonia may be related to heat stress or makes an animal more susceptible for heat. At post-mortem investigation, cattle that died of heatstroke showed: sunken eyes, a core body temperature > 43 °C, epicardial ecchymoses, severe acute diffuse pulmonary congestion and oedema. They also found that *Bos taurus* cattle were more susceptible to heat than *Bos indicus* cattle (Norris et al., 2003).

In short, we found a heat stress effect in newborn calves, preweaned calves and lactating cattle. Heat stress in young calves will cause dehydration, reduced feed intake and compromises the immune system (Broucek et al., 2009). An example that could cause this heat stress is the combination of high temperatures and young calves in calf hutches. These hutches lack climate-control options, which causes the temperature to rise. Unfortunately, during high temperatures calves are often overlooked and receive little attention for heat stress relief (Carter et al., 2014). The lack of attention during high temperatures can have possible economic effects in terms of production losses (Carter et al., 2014). Lactating cows were also sensitive to heat stress because of milk production, gestation and fermentation which all produce a lot of metabolic heat (Kadzere et al., 2002). The estimated statistical TNZ of -4.0–16.8 °C_{THI} for lactating cattle was somewhat wider than an estimated TNZ for adult dairy cattle of 5–16 °C (Gordon, 2005). The latter range is based on physiology, and the data-driven, statistical estimate used in this study is based on outdoor temperatures; in winter, these will certainly be lower than temperatures in stables. Mitigation strategies to relieve heat stress are broadly investigated and can consist of many factors, e.g., providing shade, modifying the diet, increase the amount of drinking water, increase ventilation and the usage of sprinklers and fan cooling (Fournel et al., 2017).

4.3. Cold stress and mortality

Cows are well-insulated and produce a lot of metabolic heat. Therefore, cold stress is mainly a problem caused by a depletion of energy storages in the body or a too low energy intake (feed) resulting in not enough heat production (Webster, 1974). In newborn calves, brown adipose tissue (non-shivering thermogenesis) contributes to a large amount of total heat production. During the first month of a calf's life, brown adipose tissue is rapidly converted to white adipose tissue. This white adipose tissue produces less heat and reacts less to noradrenaline (Alexander et al., 1975). When calves become older, the loss of brown adipose tissue and low ambient temperatures can result in cold stress. Cold-induced pathological lesions in newborn calves were found most in peripheral tissues (especially hind legs), as these tissues had most contact with the cold environment. Significant differences between cold- and noncold-stressed calves were appearance of subcutaneous oedema in the ventral sternum, subcutaneous haemorrhage in the hind legs, synovitis and haemorrhage of the synovial membranes of the hock joints, and haemorrhage into the hock joint cavities (Olson et al., 1980).

The lack of effects of cold on mortality in newborn calves in this study could indicate that Dutch farmers are taking risk-mitigating measures during periods of low temperature, as young calves are sensitive to cold stress (Olson et al., 1980). The lower critical temperature of 3–4 week old calves, depending on feed intake, ranged between 7–13 °C, with a 50% RH-level (Gonzalez-Jimenezx and Blaxter, 1962). This is in line with findings for pre-weaned calves of 15–55 days, as a lower critical temperature of 9.3 °CTHI was identified. During cold weather, it is important to help calves to keep their core body temperature constant, as they are sensitive to heat loss. Therefore, it can be important to adapt their diet, add heat lamps or provide a calf jacket (Roland et al., 2015).

4.4. Air pollution–cattle mortality

For the air pollution-cattle mortality association, mortality risks are less evident. Delayed effects were seen for O_3 at lag 0–7 and at lag 0–25 (newborn calves, pre-weaned calves, weaned calves and lactating cattle). When a two-pollutant model with NO_2 and O_3 was used, the effects on cattle mortality stayed more or less the same for both NO_2 and O_3. For PM_{10} and NH_3, almost no effects on cattle mortality were seen. This might be caused by higher local concentrations of PM_{10} and NH_3 inside stables. The influence of PM_{10} and NH_3 on performance of the animal and lung lesions was investigated in finishing pigs (Michiels et al., 2015). They showed that increasing concentration of PM_{10} resulted in a higher odds of pneumonia lesions and even more severe pneumonia lesions in pigs. The increasing concentration of NH_3 resulted in a higher odds of pleurisy lesions. When comparing the concentrations in this study to maximum ambient air pollution levels, there is a large difference in concentrations. For example, ambient air PM_{10} levels were found to be at a maximum concentration of 85.8 μg/m^3, while the concentrations in the study of Michiels et al. (2015) were on average between 2000 and 3000 μg/m^3. This indicates that for air pollution (PM_{10} and NH_3), local measurements inside stables are needed to determine whether there are effects on calf and cow mortality.

The biological link between air pollution and mortality is becoming clearer in pathophysiological terms. In humans, there are different potential mechanisms that could explain the effect of increased ambient PM-levels on cardiovascular diseases (Fiordelisi et al., 2017). For example, by direct or indirect lung inflammation, direct blood translocation and autonomic regulation of the heartrate, heart rate variability and blood pressure. An increase of 10 ppb in ambient ozone levels, caused on short-term platelet activation and an increase in blood pressure. This may be a possible mechanism in causing cardiovascular diseases (Day et al., 2017).

The difference in results in the warm and cold season may be caused by the same effects as in a human study in the Netherlands (Hoek et al., 2000): the fact that cattle spent more time outdoors during the grazing season. The results of the warm and cold season were compared to those in the study of (Cox et al., 2016b). They found acute and delayed associations for a 10 μg/m^3 increase of NO_2, O_3 and PM_{10} levels. In the warmer season, the following acute effects were seen: exposure to O_3 resulted in a 1.2% (95%CI: 0.3–2.1%) increase in mortality for lag 0–1, PM_{10} (lag 0) resulted in 1.6% (95%CI: 0.0–3.1%) increase in mortality and NO_2 (lag 0) resulted in an increased mortality of 9.2% (95%CI: 6.3–12%) and for lag 0–1 4.3% (95%CI: 1.5–7.3%). The significant cumulative effect estimate (lag 0–25) during the warm season was: 3.0% (95%CI: 0.2–6.0%) for O_3. This study has found no significant effects for O_3 during the warm season, while a significant cumulative effect over lag 0–25 was found for exposure to NO_2 in the two youngest age groups. For exposure to PM10, larger effect estimates were seen in newborn and pre-weaned calves. During the cold season, less effects of air pollution were seen. Only for exposure to O_3, a significant observed increased cattle mortality risk was found for lag 0–25: a 4.6% increase (95%CI: 2.2–7.0%) (Cox et al., 2016b). This study found, for exposure to O_3 in lactating cows, a RR of 1.04 (95%CI:1.00–1.09) for lag 0–7 and a RR of 1.08 (95%CI:1.02–1.15) for lag 0–25. These RR's are in the same order as found in the Belgian study. They did not find significant effects of exposure to NO_2. However, significant effects for newborn calves and young stock were found at lag 0 and lag 0–1.

The cumulative effects of exposure to O_3 in lag 0–7 and lag 0–25 showed a significantly increased risk for almost all age groups (except young stock). The insignificant cumulative RR's of NO_2 at lag 0–7 and lag 0–25 could be an indication for mortality displacement or harvesting.

4.5. Recommendations for future studies

The model choices in this study were based on previous research in temperature-related cattle mortality. The study population was divided into age groups, however some regional differences in climate can play a role as well. For example, Dutch coastal provinces often have cooler summers and warmer winters in comparison to the east mainland of the Netherlands. In future research, it would also be interesting and useful for other countries with a temperate maritime climate to investigate these regional differences in temperature-related mortality. Environmental factors in coastal regions can differ from the more inland regions. However, investigation of regional differences in air pollution- and temperature-related mortality was outside the scope of this paper. Further, more research on the TNZ among different age groups under different climatic conditions would be interesting. Temperature and air pollution can play a role in calf mortality on top of other stressors as weaning and changes in housing. Because a large heat effect on (newborn) calf mortality and heat stress among calves is often overlooked, high temperatures in calf hutches and heat-related calf mortality would also be promising subjects for future studies. The cumulative effects of exposure to O_3 in lag 0–7 and lag 0–25 showed a significantly increased risk for almost all age groups (except young stock). The insignificant cumulative RRs of NO_2 at lag 0–7 and lag 0–25 could be an indication of mortality displacement or harvesting. An increase in ozone seemed to have an effect on cattle mortality, but more research on this association is needed.

The results from this study are interesting and relevant for veterinarians and farmers who, with improved knowledge of temperature-related cattle mortality, can respond to weather and provide the best care for cattle in different age groups. In addition, they match the existing evidence for the relationship between temperature, air pollution and human and cattle mortality.

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