Urbanization and Livestock Disease: Evidence from Bovine Tuberculosis in Great Britain

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Abstract

Urban expansion is reshaping agricultural sections, leading to unexpected and unclear externalities to the spread of livestock disease. This paper assesses the effects of urbanization on the presence, intensity, and prevalence of bovine tuberculosis (bTB) in Great Britain. Our results suggest that while localized urbanization can slightly alleviate the bTB situations, urbanization in a larger area can aggravate them. In other words, the externalities of urbanization on local and regional livestock disease are heterogeneous. We estimate that the externalities of urbanization on bTB can result in about £1.7 million direct cattle death losses in Great Britain per year, and £11 million general economic loss each year in the UK.

Keywords: urbanization, livestock disease, bovine tuberculosis, externality

JEL Codes: Q12, Q18, R11

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1 Introduction

Livestock disease is a common threat to human society, and its patterns are reshaped by the rapid urbanization in modern history. Today, approximately 55% of the global population lives in urban areas, but this is expected to increase to 68% by 2050 (United Nations, 2018). It is recognized that this landscape evolution in human geography has led to changes in the livestock industry (Abu Hatab, Cavinato, and Lagerkvist, 2019), and theories about how urbanization affects livestock disease have been proposed (Hassell et al., 2017). A large body of literature suggests a positive relationship between urbanization and livestock disease. Human population concentration, higher livestock production, increased movement of humans and animals, increased trade, pollution, etc., are some of the potential channels through which urbanization can act as a stressor that can aggravate livestock disease (Ahmed et al., 2019; Hassell et al., 2017; Jones et al., 2013). Some literature has proposed the competing view that urbanization could mediate livestock disease through channels like higher disease prevention, detection, and management abilities, as well as changes in regulations and policies (Perry, Grace & Sones, 2013; Chakravorty, Fisher & Umetsu, 2007). Moreover, channels like land-use change, climate change, livestock production concentration, wildlife population and distribution change may have both positive and negative impacts on livestock disease or heterogeneous impacts on different diseases (Kappes et al., 2023; Mackenstedt, Jenkins & Romig, 2015; Perry, Grace & Sones, 2013; Bradley & Altizer, 2007).

However, there have been fewer quantitative studies providing evidence for any of the arguments above. Ecologists, biologists, or animal scientists usually link urbanization and livestock disease through theoretical analyses and case studies instead of statistical analyses. Although some epidemiologists provide empirical evidence linking urbanization with wildlife–livestock–human disease, much of the focus is on health risks to humans instead of livestock (Hassell et al., 2023; Blasdell et al., 2022). There is a large body of economics empirical studies surrounding topics of livestock disease or urbanization impacts, however, these two topics are usually isolated, and rare works link them together (Schaefer, Scheitrum, and Van Winden, 2022; Seeger et al., 2021; Zhao et al., 2022).

Our study empirically analyzes the impacts of urban areas on livestock disease by combining urbanization measurements and bovine tuberculosis (bTB) data in Great Britain from 2008 to 2018. We employ the property market indexes and nightlight measurements as two major proxies for urbanization, and we further use population density as an alternative proxy for robustness checks. We find that, while localized urbanization decreases the bTB presence and prevalence, the urbanization level in larger regions aggravates the bTB situation. We believe one mechanism that leads to the results is that urban areas can push away badgers (the major source of bTB infections) and usually have stricter badger control enforcements, thus they will alleviate localized bTB situations, but generate negative externalities to other herds in larger regions as they increase the density and movement of badgers in larger areas. Our findings are consistent with the field experiment results of

Donnelly et al. (2006), which show that badger culling can reduce the incidence of cattle TB breakdowns in the areas that are culled, but increases the incidence in neighboring areas. Their field experiment covers thirty trial areas with each about 100km^2 and only study about the badger culling activities (Donnelly et al., 2006), however, our analyses could cover the whole of Great Britain and further link bTB with urbanization.

Moreover, we provide monetary estimations for the urban areas' externalities on bTB. Based on our estimation, the externalities lead to about £1.7 million direct cattle death losses in Great Britain every year. And if we include indirect loss into consideration, urbanization leads to about £11 million economic loss each year in the UK through bTB.

The remainder of this paper is organized as follows. Section 2 introduces the background of bTB situations and related government policies. Section 3 presents the datasets we use. Section 4 describes the econometric strategies and provides summary statistics. Section 5 presents the empirical findings, while Section 6 provides several robustness checks. Section 7 estimates the bTB economic loss related to urbanization. Finally, Section 8 concludes with implications for policy and future research.

2 Background

Bovine tuberculosis (bTB) is a bacterial infection occurring in bovine animals that causes illness, coughing, and death. It is caused by the bacterium *Mycobacterium bovis* (*M. bovis*), and nearly all mammals are susceptible to infection to a variable degree (HAIRS, 2015). Transmission of *M. bovis* can occur between animals, from animals to humans, and, more rarely, between humans and from humans to animals (HAIRS, 2015). Previous literature shows that the presence of wild animals, like deer, brushtail possum, wild boar, and badgers, could be one of the major impediments to controlling bTB in the cattle industry (O'Brien et al., 2002; Vicente et al., 2006; Donnelly et al., 2006; Allen, Skuce & Byrne, 2018).

Since 1950, Great Britain has had an extensive surveillance testing program whereby animals are routinely tested for bTB (Atkins & Robinson, 2013). Animals that test positive for the bTB test (i.e., reactors) are compulsorily isolated and slaughtered; cleaning and disinfection are also compulsorily applied to the isolation areas after the reactor cattle have been removed. As soon as bTB is suspected or confirmed in a cattle herd, movement and milk restrictions are also automatically applied to the whole herd, and a 60-day short-interval skin testing (SIT) is triggered. This restriction status is sustained until all the required skin testing (and any other supplementary tests) are completed with negative results, which represents the bTB-free status restored in the herd[1]. Although the program helps control Bovine TB, bTB is still one of the biggest challenges for the UK cattle farming industry today, particularly in parts of Wales, and the West and Southwest of England (TBhub, 2025a). In

[1] Details of these policies and procedures can been found at: https://tbhub.co.uk/advice-during-a-tb-breakdown/actions-once-tb-is-suspected-or-confirmed/

2023, the incidence rate of cattle herd bTB in England, Scotland, and Wales was 7.3%, 0.6%, and 6.8%, respectively[1].

3 Data

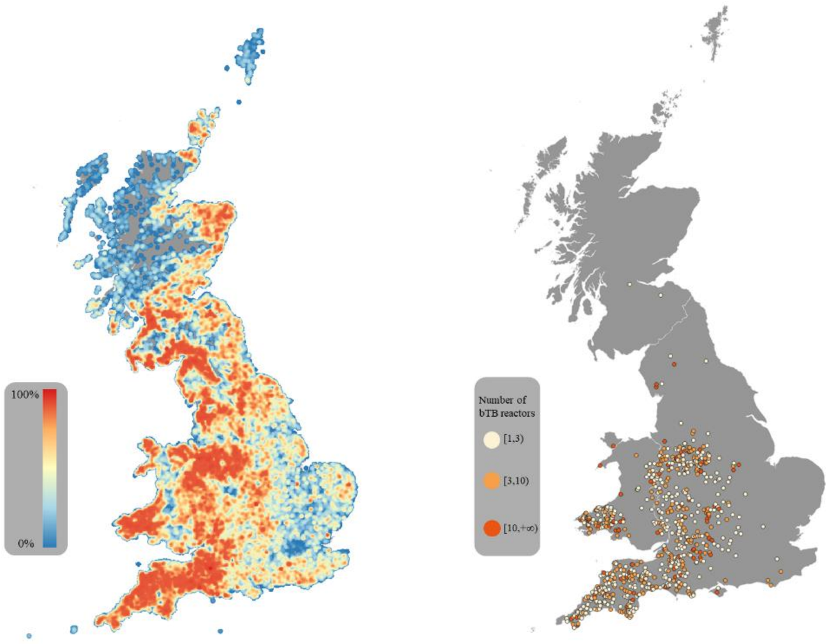
We combine three major databases to accomplish our empirical study. The Animal and Plant Health Agency (APHA) SAM database provides herd-monthly level cattle bTB records between January 2008 and December 2018 in England, Scotland, and Wales. The Visible Infrared Imaging Radiometer Suite (VIIRS) data and the HM Land Registry Price Paid Data serve as two alternatives to the proxy for urbanization. The Visible Infrared Imaging Radiometer Suite (VIIRS) data provide monthly average nightlight measurements encompassing England, Scotland, and Wales, but it's available only after January 2014. The HM Land Registry Price Paid Data provides monthly property transaction data covering only England and Wales, but it has been available since 1995. We process these three databases and integrate them into a uniform geographic information system for further analysis.

3.1 Animal and Plant Health Agency (APHA) SAM database

Animal and Plant Health Agency (APHA) SAM database records monthly information for all British beef herds, including the number of animals in the herd, the number of conducted bTB skin and blood tests, the number of positive reactors, and disease restriction status from January 2008 to December 2018. For example, in December 2018, about 8.6 million heads of cattle lived in Britain, with a heavy concentration in Western England, Wales, and Eastern Scotland (Panel (a) of Figure 1). About 0.76 million cattle received skin tests, about 20,000 had blood tests, and finally, 3551 cattle had positive bTB results. A bit different from the herd distribution, the bTB-positive reactor animals are more concentrated in Western England and Wales (Panel (b) of Figure 1).

[1] See: https://www.gov.uk/government/statistics/incidence-of-tuberculosis-tb-in-cattle-in-great-britain/quarterly-tb-in-cattle-in-great-britain-statistics-notice-december-2023

Figure 1: Spatial Distribution of Cattle and bTB reactors in Dec. 2018



(a) Cattle distribution (b) bTB reactors distribution

3.2 Visible Infrared Imaging Radiometer Suite (VIIRS) data

The Suomi National Polar-orbiting Partnership (SNPP) Visible Infrared Imaging Radiometer Suite (VIIRS) uses satellites to provide global daily measurements of nocturnal visible and near-infrared (NIR) light that are suitable for Earth system science and application studies[1]. The VIIRS Day-Night Band (DNB) data provides high-quality light measures with spatial accuracy and temporal comparability, thus, this data is widely used in recent economics studies to measure night lights (Gibson et al., 2021). Furthermore, because the lights that can be detected with satellites are mainly for urban economic activity, the night light data is well accepted as a proxy for urban development (Gibson et al., 2022; Ch, Martin, and Vargas, 2021).

This paper will use the adjusted VIIRS DNB data provided by the Earth Observation Group (EOG)[2], which is more ready-to-use as it removes interferences from the sunlit, moonlit, cloudy pixels, fires, aurora, background, etc.[3] We will use monthly composites of night lights, which are available after 2014. Notice that although the monthly VIIRS DNB provided by EOG has been available since April 2012, it excludes any data affected by stray light. A large ratio of night light data in Great Britain is excluded, especially during the summer, as the northern hemisphere has less nighttime coverage due to longer days, and the observations are strongly affected by the stray light. They also provide adjusted monthly nightlight data, which includes some of these stray-light-affected data if the radiance values could have undergone the stray-light correction procedure (Elvidge et al., 2021), but

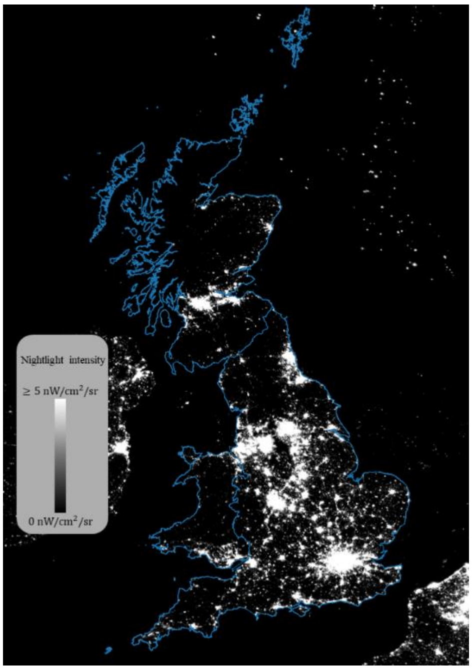
[1] Detailed introductions see: https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/VNP46A1/

[2] As of May 2024, the VIIRS DNB data provide by EOG can be downloaded through: https://eogdata.mines.edu/products/vnl/eguide.html

[3] Details adjustments see: https://eogdata.mines.edu/products/vnl/

this set is only available after 2014[1]. For a larger coverage[2] of Great Britain, we chose the set starting in 2014. It covers the earth from 180W, 75N to 180E, 65S, it has a resolution at 15 arc seconds (about 500 meters), and it provides monthly-average nightlight intensity measured in the unit $\mathrm{nW/cm^2/sr}$. Figure 2 shows the nightlight map of the GB in December 2018. We can see that it highly overlaps with British urban areas. We combine the nightlight data with the herds' records into the same geographic information system and assign the nightlight measurements to herds as a proxy for localized urbanization level.

Figure 2: Nightlight Map of The GB in Dec. 2018



3.3 HM Land Registry Price Paid Data

HM Land Registry Price Paid Data[3] records all the property sale registrations in England and Wales. Records are released each month and provide information on the sales price, street-level address of the property, date of transfer, postcode, etc., for each transaction. With these data, we observe approximately 1 million home sales each year. Since the Price Paid Data is available after 1995, it can cover the whole data period of the APHA SAM database.

The postcodes provided by Price Paid Data can reveal relatively accurate location information, so we need to adapt the postcode information to the geographic information system we are using. We apply the ONS Postcode Directory (November 2016) for the UK[4], which provides the 1-meter resolution

[1] Specifically, we use the set denoted with "vcmslcfg" and "avg_rade9h_masked". Here the "masked" means they use a set of annual "masked medians" to clear out fires and zero out the background (Elvidge et al., 2021). Details can be seen through: https://eogdata.mines.edu/products/vnl/

[2] Although this set has larger and longer coverage of Great Britain, there are still some areas in Scotland that don't have reliable monthly nightlight observations during June and July, so we have to keep them as missing observations.

[3] See: https://www.gov.uk/government/statistical-data-sets/price-paid-data-downloads#using-or-publishing-our-price-paid-data, data extracted in Aug. 2024.

[4] See: https://geoportal.statistics.gov.uk/datasets/e018152cd9a3445d89c3d751603f703b/about, data extracted in Aug. 2024.

UK Grid references (i.e., easting and northing) to every postcode in 2016, to attach spatial information to the Price Paid Data.

Although we combine the Price Paid Data and ONS Postcode Directory to locate every transaction into 1-meter resolution UK Grid references (i.e., easting and northing), we still need to further transfer the data from points to the raster layer to cover the surface of Great Britain, so we can assign the estimated urbanization measurement to every herd. To do so, we use the Kernel Density Estimator (KDE) in QGIS to generate the heatmap of property transactions as a proxy for urbanization. We set the radius of KDE as 2 kilometers[1], which assumes every transaction represents the urbanization level of adjacent areas, and this representation will diminish to zero till 2 kilometers away. We set the Kernel Shape decided by the Epanechnikov function, the reason we chose this function is discussed in Appendix A. To get smoother and continuous estimated property market "heat", we set the resolution of KDE as 100 meters. We set the weight of every transaction as its deflated transaction price, thus, more expensive property sales will represent a higher urbanization level. More details and an illustration of this method are provided in Appendix A, and a heatmap example of all the property transactions in December 2018 is shown in Figure A3. We then match the geographic information of herds with the property market heatmap and assign the localized property market "heat" to herds as an alternative proxy of urbanization level.

4 Methodology

In this section, we construct herd-level regression models to examine the effects of localized and regional urbanization on bTB presence, intensity, and prevalence in the British cattle industry.

4.1 Localized urbanization on herd-level bTB disease situation

Our model considers a herd's bTB situation as a function of its previous bTB status, the local bTB pressure, local urbanization level, the number of cattle in the herd, and the bTB testing enforcement. We also include time and herd-level fixed effects to capture herd-invariant and time-invariant unobservable factors. Our baseline regression model is as below:

$$bTB_{it} = \alpha + \beta Urbanization_{it} + \gamma bTB_{i,t-1} + \delta Pressure_{i,t-1} + \eta Cattle_{it} + \varphi Test_{it} + \lambda h_i + \mu m_t + \varepsilon_{it} \quad (1)$$

Where bTB_{it} measures the disease situation of herd i at time t. We consider three alternative methods to construct bTB_{it}. In the first construction, it is a dummy variable that indicates whether herd i has at least one positive bTB reactor at time t. We denote it with bTB_Dummy_{it}, and it captures the bTB "presence". In the second method, it is a ratio shows the share of positive bTB cattle in herd i at time t in percentage, i.e., $bTB_{it} \in [0\%, 100\%]$. We denote it with bTB_Ratio_{it}, and it

[1] We choose 2-kilometer radius based on two reasons. First, after cross checking with the nightlight maps, we notice that the nightlight measurements usually drop to zero about 1 to 3 kilometers away from the postcode locations where property transactions occurred. So we choose 2-kilometer radius to make it more consistent with the nightlight proxy. Second, Donnelly et al. (2006) show that the badger control efforts would generate negative to adjoining areas, thus, if we choose too large radius for KDE method, it might mix up the urbanization effects on urban areas with the externality on rural areas.

captures the bTB "intensity". For the third method, bTB_{it} is the number of positive bTB cattle in herd i at time t. We denote it with bTB_Number_{it}, and it captures the bTB "prevalence".

$Urbanization_{it}$ is the localized urbanization measurement of the herd i at time t. We apply two alternative proxies separately, one is the nightlight intensity measurement at about 15 arc seconds resolution (about 500 meters), and the other is the property transaction "heat" at 100-meter resolution generated using the method shown in Appendix A.

$Pressure_{i,t-1}$ is a variable that captures the local disease pressure of where herd i located at the time $t-1$. We employ the Kernel Density Estimator (KDE) in QGIS to generate the heatmap of bTB prevalence. Specifically, we use monthly bTB-positive animal reactors to generate a heatmap. We set the radius of KDE as 100 kilometers, which assumes every herd with positive bTB reactors would exert disease pressure on other herds within 100 kilometers. We set the Kernel Shape decided by Epanechnikov function, the reason we chose this function is discussed in Appendix B. We set the weight of every bTB contaminated herd as its number of positive animal reactors, thus herds with more positive bTB reactors will exert more disease pressure on other herds. The details and an illustration of this method are provided in Appendix B, and an example of the bTB disease pressure heatmap of December 2018 is shown in Figure B4. After generating the bTB heatmap, which serves as a proxy of disease pressure, we match the geocode of the herd i to the heatmap and assign the local bTB "heat" as the disease pressure $Pressure_{i,t}$. We use a one-period lagged $Pressure_{i,t-1}$ in regression to avoid endogenous issue, as bTB_{it} have impacts on the contemporary $Pressure_{i,t}$.

$bTB_{i,t-1}$ is the lagged dependent variable. $Cattle_{it}$ is the number of all the cattle in the herd i at time t. It's straightforward to think that the number of cattle in the herd influences bTB_{it}, for example, the number of bTB reactors can't exceed the total number of cattle. $Test_{it}$ measures the bTB test enforcement in the herd i at time t, and the construction of $Test_{it}$ depends on the specification of bTB_{it}. Specifically, when bTB_{it} is the dummy variable indicates if the herd has any positive bTB animal, $Test_{it}$ is also a dummy variable that indicates if the herd got any bTB test during the same period. When bTB_{it} is the ratio shows the share of positive bTB cattle in a herd i at time t, $Test_{it}$ is the ratio of total tests (including skin tests and blood tests) enforced over the total number of cattle in percentage, it could be bigger than 100% because cattle could be tested more than once or with both blood and skin tests in a month. When bTB_{it} is the number of positive bTB cattle in a herd i at time t, $Test_{it}$ is the number of total tests enforced. h_i and m_t are herd-level and year-month-level fixed effects, respectively.

4.2 Regional urbanization on herd-level bTB disease situation

After testing how localized urbanization level affects the bTB situation of cattle herds, we are still interested in whether the urbanization in larger areas has different effects on local herds. Thus, we further test the effects of the regional urbanization level. The regression model is as below

$$bTB_{it} = \alpha + \beta Urbanization_{rt} + \gamma bTB_{i,t-1} + \delta Pressure_{i,t-1} + \eta Cattle_{it} + \varphi Test_{it} + \lambda h_i + \mu m_t + \varepsilon_{it} \quad (2)$$

Where most variables have the same definition used in Section 4.1, the only difference is that we include the regional urbanization measurement $Urbanization_{rt}$ instead of localized urbanization. The construction of regional urbanization is the average localized urbanization measurement of all herds located in the same Local Authority District (LAD) r at time t, i.e., $Urbanization_{rt} = \frac{\sum_{herd\ i\ located\ in\ LAD\ r\ at\ time\ t} Urbanization_{it}}{number\ of\ herds\ located\ in\ LAD\ r\ at\ time\ t}$. Thus, the regional urbanization levels we defined in this section are LAD-level measurements for urbanization. A map of the 2016 Local Authority Districts (LADs) in provided in Figure E1.

4.3 Summary statistics

In this section, we provide summary statistics for the variables used in our analyses. Although the APHA SAM database covers England, Wales, and Scotland from 2008 to 2018, the VIIRS data and HM Land Registry Price Paid Data are more spatiotemporally limited. Thus, we further extract two subgroups of APHA SAM data to match with VIIRS data and HM Land Registry Price Paid Data separately. Two cohorts of data are finally created for further analyses. Specifically, the first cohort matches the APHA SAM database (herd data) with VIIRS data (nightlight data) and forms a dataset with 5,024,081 observations covering England, Wales, and Scotland from Jan. 2014 to Dec. 2018. And the second cohort matches the APHA SAM database with property market heatmaps generated from HM Land Registry Price Paid Data and forms a dataset with 11,813,973 observations covering England and Wales from Jan. 2008 to Dec. 2018. The detailed summary statistics of these two cohorts are shown in Table 1.

Table 1: Summary Statistics

Cohort with the nightlight as the urbanization measurements

Coverage: Covering England, Wales, and Scotland from Jan. 2014 to Dec. 2018

Number of observations: 5,024,081

Variables	Alternatives	Definitions	Mean	Std. dev.	Min	Max
bTB	Dummy	Equals to 1 if there's at least one bTB reactor in the herd	0.0096	0.0973	0	1
	Ratio	The ratio of bTB reactors to the head of cattle in the herd in percentage	0.0275	0.8670	0	100
	Number	Number of bTB reactors	0.0363	0.7683	0	352
$Urbanization$	Localized Nightlight	Monthly average localized nightlight measurement	1.1867	3.1450	0	457.65
	Regional Nightlight	The average of nightlight measurements of all the herds within the same LAD	1.1867	1.7244	0	100.95
$Pressure$	-	local disease pressure generated by QGIS	266.5999	253.9095	0	1172.11
$Cattle$	-	Number of cattle in the herd	99.3925	183.7856	0	7824
$Test$	Dummy	Equal to 1 if there's at least one bTB test has been conducted	0.1281	0.3342	0	1
	Ratio	The ratio of the total number of any kind of tests to the number of cattle in percentage	6.6236	100.4416	0	105900
	Number	Number of total tests conducted	9.4286	60.1823	0	5020

Cohort with the property market heat as the urbanization measurements

Coverage: Covering England and Wales from Jan. 2008 to Dec. 2018

Number of observations: 11,813,973

Variables	Alternatives	Definitions	Mean	Std. dev.	Min	Max
bTB	Dummy	Equals to 1 if there's at least one bTB reactor in the herd	0.0092	0.0954	0	1
	Ratio	The ratio of bTB reactors to the head of cattle in the herd in percentage	0.0283	0.9554	0	100
	Number	Number of bTB reactors	0.0328	0.6970	0	352
$Urbanization$	Localized Property market heat	Monthly property market heat generated by QGIS	0.3976	1.5072	0	457.05
	Regional Property market heat	The average of property market heat measurements of all the herds within the same LAD	0.3976	1.1354	0	396.06
$Pressure$	-	local disease pressure generated by QGIS	298.3764	250.3600	0	1172.11
$Cattle$	-	Number of cattle in the herd	76.7569	151.1299	0	5956
$Test$	Dummy	Equal to 1 if there's at least one bTB test been conducted	0.1123	0.3157	0	1
	Ratio	The ratio of the total number of any kind of tests to the number of cattle in percentage	5.8793	114.2641	0	114700
	Number	Number of total tests conducted	7.6526	51.4784	0	21100

5 Empirical results

We estimate the coefficients in Equation (1) and Equation (2) to assess the impacts of localized and regional urbanization levels on the bTB situation of cattle herds in Great Britain. We analyze the bTB situation through three dimensions, i.e., disease presence, intensity, and cases. We use nightlight measurement and property market heat as two proxies of urbanization for robustness. Table 2 reports the results from analyzing the impacts of localized urbanization level on bTB disease, and Table 3 reports the results from analyzing the impacts of regional urbanization. Broadly speaking, our empirical results show that localized urbanization decreases the bTB presence and prevalence, however, the regional urbanization level in larger areas aggravates the situation of bTB.

5.1 Impacts of localized urbanization on herd-level bTB disease situations

We first report the results of testing the impacts of localized urbanization levels on herds' bTB situations in Table 2. Columns (1)-(3) report the results of using nightlight measurements as the proxy for urbanization, and Columns (4)-(6) report the ones using property market heat as the proxy. Moreover, Columns (1) and (4) show the results of setting bTB_Dummy as the dependent variable to test the impacts on bTB presence. Columns (2) and (5) use bTB_Ratio as the dependent variable to test the impacts on bTB intensity. And Column (3) and (6) use bTB_Number as the dependent variable to test the impacts on bTB prevalence. Specifically, when using nightlight measurements as the proxy, we find that localized urbanization level can statistically significantly decrease the bTB presence. If the nightlight measurement increases by 1 $\mathrm{nW/cm^2/sr}$, the possibility of the herds getting bTB infection decreases by 0.000032. Notice that the average possibility of a herd getting bTB is 0.0096, so this means that a 1 $\mathrm{nW/cm^2/sr}$ increase in nightlight measurement will make the herd 0.3% less likely to get bTB. When using property market heat as the proxy, we see that if the property market heat increases by 1 unit, the number of positive bTB reactors in a herd will statistically significantly decrease -0.00018. Notice that the average number of bTB reactors in a herd is 0.0328, so this means that a 1 unit increase of property measurement will make the number of bTB reactors in a herd drop about 0.6%. For estimators of the rest specifications, although not statistically significant, they are usually negative. Generally speaking, we find that increasing localized urbanization levels will decrease the bTB presence and prevalence of cattle herds.

Table 2: Localized urbanization on bTB situations

	Nightlight			Property		
	(1)	(2)	(3)	(4)	(5)	(6)
	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Number_{it}	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Number_{it}
$Urbanization\_Nightlight_{it}$	-0.000032*	-0.000003	0.000030	-	-	-
	(0.000020)	(0.000242)	(0.000108)	-	-	-
$Urbanization\_Property_{it}$				-0.000004	-0.000025	-0.000181**
				(0.000015)	(0.000159)	(0.000090)
$Pressure_{i.t-1}$	0.000007***	0.000011*	0.000042***	0.000013***	0.000046***	0.000060***
	(0.000001)	(0.000007)	(0.000007)	(0.000000)	(0.000006)	(0.000004)
$Cattle_{it}$	0.000036***	0.000047**	0.000511***	0.000037***	0.000033**	0.000413***
	(0.000002)	(0.000020)	(0.000047)	(0.000002)	(0.000014)	(0.000029)
$bTB\_Dummy_{i,t-1}$	-0.004795***			0.027520***		
	(0.001776)			(0.001241)		
$Test\_Dummy_{it}$	0.063616***			0.071899***		
	(0.000549)			(0.000512)		
$bTB\_Ratio_{i,t-1}$		0.012718			0.040646***	
		(0.010302)			(0.006792)	
$Test\_Ratio_{it}$		0.002075***			0.002098***	
		(0.000438)			(0.000333)	
$bTB\_Number_{i,t-1}$			0.000109			0.031671**
			(0.007157)			(0.013378)
$Test\_Number_{it}$			0.001211***			0.001243***
			(0.000062)			(0.000053)
Constant	-0.004050***	0.005819*	-0.037158***	-0.005859***	-0.001341	-0.027375***
	(0.000353)	(0.003222)	(0.005334)	(0.000233)	(0.002158)	(0.002821)
Herd Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year-Month Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	5024081	5024081	5024081	11813973	11813973	11813973

Cluster standard errors in parentheses. Standard errors are clustered at the herd level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

5.2 Impacts of regional urbanization on herd-level bTB disease situations

Table 3 reports the regression results of evaluating the impacts of regional urbanization on herds' bTB situations. Similarly, Columns (1)-(3) report the results of using nightlight measurements as the proxy for urbanization, and Columns (4)-(6) report the ones using property market heat as the proxy. Columns (1) and (4) show the results of setting bTB_Dummy as the dependent variable to test the impacts on bTB presence. Columns (2) and (5) use bTB_Ratio as the dependent variable to test the impacts on bTB intensity. And Columns (3) and (6) use bTB_Number as the dependent variable to test the impacts on bTB cases.

Broadly speaking, we find that regional urbanization level will aggravate herds' bTB situations, which is opposite to the impacts of localized urbanization. Specifically, when using nightlight measurements as the proxy, we find that localized urbanization level can statistically significantly increase the bTB cases in a herd. If the nightlight measurement increases by 1 $nW/cm^2/sr$, the number of bTB cases in a herd will increase 0.000867. Notice that the average bTB cases in a herd is 0.0363, so this means that a 1 $\mathrm{nW/cm^2/sr}$ increase in nightlight measurement will make the bTB cases in a herd increase by 2.4%. When using property market heat as the proxy, we see that the regional urbanization level has a positive relationship with all three bTB measurements. If the property market heat increases by 1 unit, the possibility of herd tested positive with bTB will increase 0.000034, the ratio of positive reactors in a herd will increase 0.000387%, and the real cases of bTB reactors will increase 0.000316. After comparing with the herds' average bTB situation measurements, our results indicate that if the regional property market heat increases 1 unit, the possibility of a herd tested positive with bTB will increase by 0.4%[1], the ratio of positive reactors in a herd will increase by 1.4%[2], and the number of positive bTB reactors in a herd will increase by 1.0%[3].

Table 3: Regional urbanization on bTB situations

	Nightlight			Property		
	(1)	(2)	(3)	(4)	(5)	(6)
	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Number_{it}	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Number_{it}
$Urbanization\_Nightlight_{rt}$	-0.000048	0.000440	0.000867*	-	-	-
	(0.000065)	(0.000587)	(0.000498)	-	-	-
$Urbanization\_Property_{rt}$				0.000034*	0.000387**	0.000316**
				(0.000019)	(0.000170)	(0.000129)
$Pressure_{i,t-1}$	0.000007***	0.000011*	0.000042***	0.000013***	0.000046***	0.000060***
	(0.000001)	(0.000007)	(0.000007)	(0.000000)	(0.000006)	(0.000004)
$Cattle_{it}$	0.000036***	0.000047**	0.000511***	0.000037***	0.000033**	0.000413***
	(0.000002)	(0.000020)	(0.000047)	(0.000002)	(0.000014)	(0.000029)
$bTB\_Dummy_{i,t-1}$	-0.004795***			0.027520***		
	(0.001776)			(0.001241)		
$Test\_Dummy_{it}$	0.063616***			0.071899***		
	(0.000549)			(0.000512)		
$bTB\_Ratio_{i,t-1}$		0.012718			0.040646***	
		(0.010302)			(0.006792)	
$Test\_Ratio_{it}$		0.002075***			0.002098***	
		(0.000438)			(0.000333)	
$bTB\_Number_{i,t-1}$			0.000108			0.031671**
			(0.007157)			(0.013378)
$Test\_Number_{it}$			0.001211***			0.001243***
			(0.000062)			(0.000053)
Constant	-0.004032***	0.005301*	-0.038137***	-0.005872***	-0.001477	-0.027540***
	(0.000360)	(0.003205)	(0.005298)	(0.000234)	(0.002158)	(0.002822)
Herd Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year-Month Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	5024081	5024081	5024081	11813973	11813973	11813973

Cluster standard errors in parentheses. Standard errors are clustered at the herd level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

[1] $0.4\% \approx 0.000034 \div 0.0092 * 100\%$
[2] $1.4\% \approx 0.000387\% \div 0.0283\% * 100\%$
[3] $1.0\% \approx 0.000316 \div 0.0328 * 100\%$

6 Robustness checks

We conduct several robustness checks to test the consistency of our findings with alternative urbanization proxies and model specifications. Section 6.1 re-estimates the effects of regional urbanization on bTB situations using population density as an alternative proxy for urbanization, and, as a supplementary, we further use historical population density as an instrumental variable (IV) to avoid potential endogeneity issues. Section 6.2, instead of estimating the impacts of localized and regional urbanization separately, includes both measurements in one regression to estimate the effects simultaneously. Section C shows our results with some other alternative specifications. Specifically, Section C.1 reports the results without fixed effects or only with one-way fixed effects. Section C.2 includes the interaction term of urbanization measurements and lagged bTB pressure. Section A1.2 tests the specifications with some dynamic variables.

6.1 Using population density and the IV approach

While nightlight and property transactions are often used as proxies for urbanization recently, population density is a more traditional and widely used measurement for urbanization (Ch, Martin, and Vargas, 2021; Dong and Schaefer, 2025; Michaels, Rauch, and Redding, 2012; Davis, 2015). However, we don't apply the population density as the primary proxy for urbanization in this paper for two reasons. First, the available population density data have lower spatiotemporal resolution. We get the official population estimates data from the UK's Office for National Statistics[1]. This data covers the whole of Great Britain from 1981 to 2019, however, it only provides mid-year population estimation for Local Authority Districts using the April 2020 administrative geography. Thus, while property transaction data and nightlight data can provide monthly urbanization measurements with less than 500-meter resolutions, the annual LAD-level population densities would be insufficient, especially when testing the impact of localized urbanization. Second, using population density as the proxy for urbanization to study the effects on bTB situations may bring some endogenous issues. For example, although we use fixed effect estimations to control for unobserved factors, omitted variables like pollution, beef prices, and public expenditure may have relationships with both bTB situations and local populations, which may sabotage our findings. Another example, using population data may bring "reverse causality" issues as the bTB situations may also affect the local population. Thus, we choose to use nightlight data or property transaction data as baseline approaches because they can better avoid potential endogenous issues.

Despite the issues we discussed above regarding using population density as the proxy for urbanization, we provide a robustness check with it to align with previous literature and further support our findings. With the mid-year population estimates data from the UK's Office for National Statistics and the LADs' areas of 2020 administrative geography, we calculated the annual population

[1] See: https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/adhocs/13221populationestimatesbylocalauthoritiesofgreatbritainmid1981tomid2019. Data extracted in Feb. 2025.

density estimates in the unit of persons per square kilometre for every LAD from 1981 to 2019. We first use an OLS regression similar to Equation (2) to provide baseline results. Furthermore, to deal with the potential endogenous issues discussed above, we employ the 2SLS method with historical population densities from 1988 to 1998 as instrumental variables for the population densities of our study period, which is from 2008 to 2018. Notice that the population density data is only available at the LAD level, thus, we are only able to test the effects of regional urbanization. The results are shown in Table 4. Columns (1) to (3) report the results with the OLS approach, and Columns (4) to (6) report the ones with the 2SLS approach. We can see that the OLS approach doesn't generate any statistically significant results, but after employing the IV approach, we get a statistically significant relationship between regional population density and herds' bTB reactors. The results suggest that when the regional population density increases 1 person per square kilometer, the expected number of bTB reactors in a herd will increase 0.00001641. Notice that the average number of bTB cattle in a herd of this cohort is 0.0279, and the average population density is about 225 people per square kilometer. Thus, our estimators suggest that if the population density increases by 10%, the number of bTB cattle will increase by about 1.3%[1]. These results are consistent with our baseline findings, which further support the positive relationship between regional urbanization and bTB severity.

[1] $1.3\% \approx 0.00001641 * (225 * 10\%) \div 0.0279 * 100\%$

Table 4: Regional urbanization measured by population density on bTB situations

	OLS Approach			2SLS Approach		
	(1)	(2)	(3)	(4)	(5)	(6)
	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Number_{it}	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Number_{it}
$Urbanization\_Pop.dens._{rt}$	-0.00000083	-0.00000002	0.00000399	-0.00000111	-0.00000015^{*}	0.00001641^{*}
	(0.00000075)	(0.00000005)	(0.00000386)	(0.00000124)	(0.00000009)	(0.00000857)
$Pressure_{i,t-1}$	0.00001255^{***}	0.00000043^{***}	0.00005784^{***}	0.00001255^{***}	0.00000043^{***}	0.00005773^{***}
	(0.00000048)	(0.00000006)	(0.00000374)	(0.00000048)	(0.00000006)	(0.00000374)
$Cattle_{it}$	0.00003142^{***}	0.00000027^{**}	0.00034053^{***}	0.00003142^{***}	0.00000027^{**}	0.00034054^{***}
	(0.00000171)	(0.00000012)	(0.00002408)	(0.00000171)	(0.00000012)	(0.00002408)
$bTB\_Dummy_{i,t-1}$	0.02810623^{***}			0.02810624^{***}		
	(0.00124053)			(0.00124053)		
$Test\_Dummy_{it}$	0.06935620^{***}			0.06935625^{***}		
	(0.00049366)			(0.00049366)		
$bTB\_Ratio_{i,t-1}$		0.04139388^{***}			0.04139388^{***}	
		(0.00679759)			(0.00679758)	
$Test\_Ratio_{it}$		0.00206464^{***}			0.00206464^{***}	
		(0.00032312)			(0.00032312)	
$bTB\_Number_{i,t-1}$			0.03251488^{**}			0.03251498^{**}
			(0.01319175)			(0.01319174)
$Test\_Number_{it}$			0.00124030^{***}			0.00124030^{***}
			(0.00005224)			(0.00005224)
Constant	-0.00479364^{***}	-0.00000188	-0.02480253^{***}	-0.00407049^{***}	0.00005508	-0.02301357^{***}
	(0.00025881)	(0.00002111)	(0.00255306)	(0.00042236)	(0.00004015)	(0.00380713)
Herd Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year-Month Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	13971493	13971493	13971493	13971493	13971493	13971493

Cluster standard errors in parentheses. Standard errors are clustered at the herd level.

The 2SLS approach passes the underidentification test and weak IV test.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

6.2 Including both localized and regional urbanization proxies into one regression

We estimate the impacts of localized and regional urbanization levels on bTB situations separately in our baseline regressions, because these two variables may lead to an underestimate of each other. In this section, we provide a robustness check to include them in one econometrics model and estimate their impacts simultaneously, this approach will help avoid the potential omitted variable issue resulting from the separated estimations. This approach can be illustrated by the following equation:

$$bTB_{it} = \alpha + \beta_1 Urbanization_{it} + \beta_2 Urbanization_{rt} + \gamma bTB_{i,t-1} + \delta Pressure_{i,t-1} + \eta Cattle_{it} + \varphi Test_{it} + \lambda h_i + \mu m_t + \varepsilon_{it} \quad (3)$$

The results of this approach are shown in Table 5. Columns (1) to (3) show the result of using nightlight as the proxy for urbanization, and Columns (4) to (6) report the ones with property market heat as the proxy. Generally speaking, although slightly different, the results are still consistent and have the same direction as our baseline approaches. While the estimations of the localized and regional nightlight variables get slightly smaller and less significant compared to the baseline results, the estimations of property transaction variables get much bigger and more significant.

Table 4: Localized and regional urbanization on bTB situations

	Nightlight			Property		
	(1)	(2)	(3)	(4)	(5)	(6)
	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Number_{it}	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Number_{it}
$Urbanization\_Nightlight_{it}$	-0.000030	-0.000051	-0.000060	-	-	-
	(0.000020)	(0.000265)	(0.000111)	-	-	-
$Urbanization\_Nightlight_{rt}$	-0.000019	0.000488	0.000923*	-	-	-
	(0.000068)	(0.000658)	(0.000517)	-	-	-
$Urbanization\_Property_{it}$	-	-	-	-0.000025	-0.000255	-0.000459***
	-	-	-	(0.000022)	(0.000221)	(0.000132)
$Urbanization\_Property_{rt}$	-	-	-	0.000059*	0.000642**	0.000776***
	-	-	-	(0.000031)	(0.000263)	(0.000204)
$Pressure_{i,t-1}$	0.000007***	0.000011*	0.000042***	0.000013***	0.000046***	0.000060***
	(0.000001)	(0.000007)	(0.000007)	(0.000000)	(0.000006)	(0.000004)
$Cattle_{it}$	0.000036***	0.000047**	0.000511***	0.000037***	0.000033**	0.000413***
	(0.000002)	(0.000020)	(0.000047)	(0.000002)	(0.000014)	(0.000029)
$bTB\_Dummy_{i,t-1}$	-0.004795***			0.027520***		
	(0.001776)			(0.001241)		
$Test\_Dummy_{it}$	0.063616***			0.071899***		
	(0.000549)			(0.000512)		
$bTB\_Ratio_{i,t-1}$		0.012718			0.040646***	
		(0.010302)			(0.006792)	
$Test\_Ratio_{it}$		0.002075***			0.002098***	
		(0.000438)			(0.000333)	
$bTB\_Number_{i,t-1}$			0.000108			0.031671**
			(0.007157)			(0.013378)
$Test\_Number_{it}$			0.001211***			0.001243***
			(0.000062)			(0.000053)
Constant	-0.004029***	0.005305*	-0.038132***	-0.005872***	-0.001477	-0.027540***
	(0.000360)	(0.003206)	(0.005298)	(0.000234)	(0.002158)	(0.002822)
Herd Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year-Month Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	5024081	5024081	5024081	11813973	11813973	11813973

Cluster standard errors in parentheses. Standard errors are clustered at the herd level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

7 Economic loss estimation

Our empirical results suggest that while localized urbanization can alleviate bTB situations, regional urban expansion can aggravate the disease situation. With this evidence showing the externalities generated from urbanization, a more attractive topic is estimating the monetary loss or gain of these externalities. To do so, we construct a counterfactual scenario to evaluate the cattle death loss results from urbanization. We first reset the localized and regional urbanization level of all the herds to zero and calculate the counterfactual changes of cattle been slaughtered[1] in every herd. The detailed illustration of this step is provided in Appendix D. With the counterfactual changes of slaughtered cattle, we further calculate the counterfactual slaughtered cattle and compare them with the real ones. This comparison is illustrated in Figure 3. We can see that, in England, Wales, and Scotland, from Jan. 2014 to Dec. 2018, averagely there were 3309 cattle been slaughtered because of bTB in each month, and there would be about 141 fewer slaughtered cattle per month if we had set the urbanization level to zero. This change accounts for about 4.27%[2] decreasing in the number of cattle been slaughtered because of bTB. For these cattle been slaughtered because of bTB, the UK government will pay compensation based upon average livestock market prices for the relevant categories. If we bring in these monthly disclosed compensation rates[3] into calculation, we can get the estimated bTB death loss results from urbanization. Figure 4 shows the estimation of these death losses. From Jan. 2014 to Dec. 2018, averagely the urbanization leads to about £150,000 monetary death loss per month in Great Britain, corresponding to about £1.7 million death loss annually.

Although we provide the urbanization-affected bTB death loss estimations, this is only a small part of the total bTB economic loss resulting from urbanization. As the UK government implements the bTB eradication strategy as we discussed in Section 2, the policy costs taxpayers millions of pounds per annum in wildlife control, testing, research, and slaughter compensation (Godfray et al., 2018). Besides the direct government payment, bTB outbreaks also lead to economic losses for the cattle industry from channels like cattle slaughter, extra labor, movement and trade restrictions, and farmers' mental stress.[4] Thus, to better estimate the general economic loss of urbanization-affected bTB, we collect the information for government payments and farmer losses from many sources. Table 5 summarizes the data we collected. The data about UK government payments is sufficient, which suggests about £150 million annual cost in recent years, and this cost has increased in the past decades (APHA, 2023; Defra, 2008; Defra 2009; Defra 2010; Defra, 2011; Defra, 2022). However, we only get limited cost estimations for the cattle industry in England, which is between £50 million to £75 million each year. With the limitation of data availability, we can't provide a precise evaluation of urbanization externalities on bTB economic costs. However, we'd like to provide some rough estimations based on the data we have and with more assumptions. First, if we combine the information provided by Godfray et al. (2018) and Defra (2014), we can estimate that the cost for the England cattle industry is around 70% to 75%[5] comparing to the cost for England taxpayers. Second,

[1] In our baseline empirical settings, we use bTB reactors information to evaluate the impacts of urbanization on bTB prevalence. However, when calculating the death loss, we use the number of cattle been slaughtered because of bTB. This is because the numbers of cattle been slaughtered are not always equal to the numbers of positive bTB reactors. According to the UK government, not only the cattle been confirmed of bTB affection (bTB positive reactors) should be slaughtered, those are suspected of having bTB are also slaughtered. Thus the number of cattle been slaughtered would sometimes exceed the number of reactors.

[2] 4.27% ≈141/3309*100%

[3] See: https://www.gov.uk/government/publications/bovine-tb-historical-compensation-value-tables. Data extracted in Mar. 2025. Specifically, we use the monthly average compensation rate of non-pedigree beef sector cattle over 20 months and over (not calved for the female). This application aligns with Schaefer, Scheitrum, and van Winden (2022).

[4] See: https://www.gov.uk/government/statistics/incidence-of-tuberculosis-tb-in-cattle-in-great-britain/quarterly-tb-in-cattle-in-great-britain-statistics-notice-december-2024

[5] 70% ≈£50 million /£70 million *100%; 75% =£75 million /£100 million *100%

we further assume this ratio can be applied to the whole UK, and we use the data provided by APHA (2023), we can calculate that the bTB losses for the UK cattle industry are between £105 million to £112.5 million each year[1]. Finally, since in this section we get an estimation of a 4.27% decrease in bTB cattle slaughtered with a zero-urbanization counterfactual scenario, we further assume this ratio can be applied to the general economic losses estimations. Thus, we estimate that the urbanization-led bTB general economic loss in the UK is about £11 million per year, where about £6.4 million is paid by taxpayers and £4.8 million falls into the cattle industry[2].

Generally, the urban areas exert negative externalities on the UK cattle industry through bTB. Based on our estimation, the externalities lead to about £1.7 million direct cattle death losses in Great Britain every year. If we further include indirect loss into consideration, urbanization leads to about £11 million economic loss each year in the UK through bTB.

[1] £105 million =£150 million *70%; £112.5 million =£150 million *75%

[2] £11 million ≈£150 million *4.27% +£105 million *4.27%; £11 million ≈£150 million *4.27% +£112.5 million *4.27%; £6.4 million ≈£150 million *4.27%; £4.8 million =£11 million -£6.4 million

Figure 3: The effects of urbanization on cattle been slaughtered

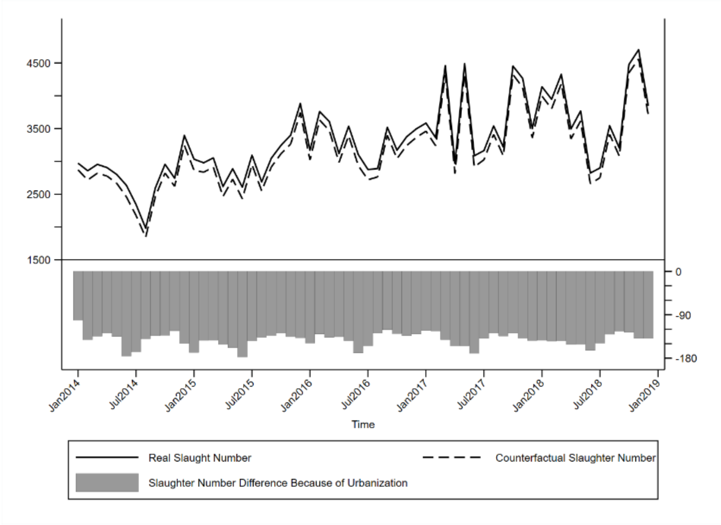


Figure 4: Cattle death loss because of urbanization

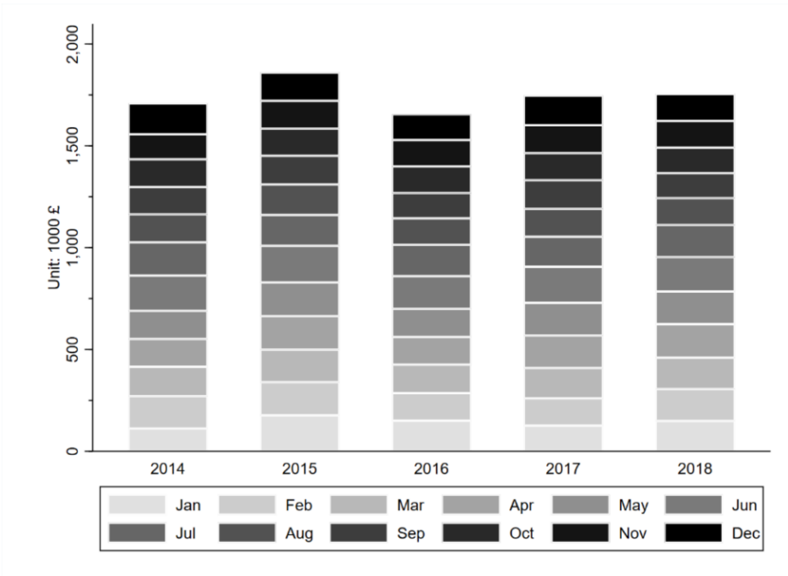


Table 5: Economic loss of bTB

Financial year or report year	Geographical coverage	Cost for UK taxpayers	Cost for cattle industry	Data sources
Reported in 2025	England	About £100 million every year	-	TBhub (2025b)
Reported in 2023	UK	Averagely £150 million per annum	-	APHA (2023)
Financial year 2022/23	Northern Ireland	About £53 million	-	DAERA (2024)
Financial years from 2012 to 2022	England	Averagely £100 million per annum	-	Defra (2022)
The five financial years between 2016/17 and 2020/21	Northern Ireland	Averagely £38.4 million per annum	-	DAERA (2024)
Reported in 2018	England	Averagely £70 million per annum	Averagely £50 million per annum	Godfray et al. (2018)
Reported in 2014	England	Averagely £100 million per annum	Averagely £75 million per annum	Defra (2014)
Financial years from 1998 to 2010	Great Britain	Averagely £71 million per annum	-	Defra, 2008; Defra 2009; Defra 2010; Defra, 2011

Note: If one data source reports economic costs for several financial years separately, we calculate the average annual costs and report them in the table to save space.

8 Conclusion and Discussion

As urban environments expand, their externalities on agricultural sections are becoming more significant but also more intricate. This paper evaluates the externalities from the perspective of livestock disease. We assess the effects of localized and regional urbanization levels on the bTB presence, intensity, and prevalence in the context of the British cattle industry. In the dataset we constructed, we use nightlight, property market, and population density measurements as alternative proxies for urbanization. And we further combine them with monthly herd-level bTB records for all cattle herds in Great Britain from Jan. 2008 to Dec. 2018.

Our results indicate that while bTB situations of herds can be slightly alleviated by localized urbanization, they are aggravated if regional urbanization in relatively larger areas increases. Based on our estimation, urban areas' externalities contribute about 4.27% of total bTB death loss, which corresponds to about £1.7 million cattle death losses in Great Britain and about £11 million overall economic loss in the UK per year.

Policy implications are many. As urbanization brings visible economic benefits to the agricultural industry through economic growth, value chain, market access, etc., the effects on animal health are usually neglected. While urbanization may lower the livestock disease outbreaks in local areas, it may lead to larger negative externalities to nearby areas. Policymakers need to be more careful in planning human economic activities near livestock to alleviate the potential health risks to farm animals, which will also help control human health risks under zoonotic diseases. The government needs to zone different industries through holistic urban-suburban-rural thinking to maximize the economic benefit of urbanization. Adjusting farm management practices to better cope with ongoing urbanization in nearby areas is always a complex and tough problem for farmers, so our study also provides insights for farmers in farm allocation, wildlife control, and animal disease control.

Our work also brings some unsolved research questions for further studies. We empirically provide evidence to link urbanization and bTB in the cattle industry. And align with Donnelly et al. (2006), we propose a mechanism that the urban areas have stronger badger culling forces and can push away badgers to nearby areas, thus leading to the heterogeneous effects on localized and regional areas' bTB situations. However, we couldn't further provide direct evidence for this proposed mechanism since we don't have enough micro-level data for the badgers' spatiotemporal distributions. Studies are still needed to explore the linkage mechanisms of urbanization and livestock disease. Moreover, our study focuses on cattle bTB, of which wildlife is the major infection source, but the impacts of population concentration on the spread of other diseases, especially those zoonoses with human beings as a considerable infection source, are still unclear.

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Appendix A. Construction of property transaction heatmaps

We employ monthly Price Paid Data with the Kernel Density Estimator (KDE) in QGIS to generate heatmaps of property transactions in England and Wales. The basic idea of our construction is that a property transaction represents some "heat" level of the nearby property market, and multiple heats generated by multiple transactions can be spatially aggregated if their areas of influence have overlaps. Thus, with all the property transaction data in England and Wales, we can generate a heatmap for the property market activities, which can be considered as a measurement of urban areas.

In the Kernel Density Estimator (KDE) program in QGIS, we set the weight of every transaction (which represent the "heat" level) as its price in million £ deflated by the Consumer Prices Index, including owner occupiers' Housing costs (CPIH)[1]. Thus more expensive property sales will represent a higher urbanization level. We set the radius of KDE as 2 kilometers[2], which assumes every transaction represents the urbanization level of adjoining areas within 2 kilometers. To get smoother and continuous estimated property market "heat", we set the resolution of KDE as 100 meters. We set the Kernel Shape decided by the Epanechnikov function, which is shown as below:

$$K(u) = \frac{3}{4}(1 - u^2), u \in [-1,1] \quad \text{(A1)}$$

By employing the Epanechnikov function into our property market heat context, it can be rewrite as:

$$H_{ij} = KWI\frac{3}{4}\left(1 - \left(\frac{d_{ij}}{radius}\right)^2\right), |d_{ij}| \le radius \quad \text{(A2)}$$

Where H_{ij} is the property market heat that property transaction i generates on location j, K is a constant, W is the weight, I represents intensity. Notice that in QGIS, it has an option to set "weight", this means different from our W in the function. The "weight" in QGIS can be considered as the product of $K * W * I$. d_{ij} is the distance between property transaction i and location j. $radius$ is the farthest distance that a property transaction can exert "heat". By inputting our settings, the function is:

$$H_{i,j,t} = Price_{i,t} * \frac{3}{4} * \left(1 - \left(\frac{d_{i,j,t}}{2}\right)^2\right), d_{i,j,t} \le 2 \quad \text{(A3)}$$

Where $Price_{i,t}$ is the transaction price of property transaction i occurred at time t. This transaction price is in million £ and is deflated with CPIH.

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[1] See: https://www.ons.gov.uk/economy/inflationandpriceindices/timeseries/l522/mm23. Data extracted in Oct. 2024.

[2] We choose 2-kilometer radius based on two reasons. First, after cross checking with the nightlight maps, we notice that the nightlight measurements usually drop to zero about 1 to 3 kilometers away from the postcode locations where property transactions occurred. So we choose 2-kilometer radius to make it more consistent with the nightlight proxy. Second, Donnelly et al. (2006) show that the badger control efforts would generate negative to adjoining areas, thus, if we choose too large radius for KDE method, it might mix up the urbanization effects on urban areas with the externality on rural areas.

Thus, for a specific point j, the estimated property market heat is:

$$U_{j,t} = \sum_{i=1}^{m} Price_{i,t} * \frac{3}{4} * \left(1 - \left(\frac{d_{i,j,t}}{2}\right)^2\right) \quad \text{(A4)}$$

Where m is the total number of transaction that occurred within 2 kilometers of point j at time t.

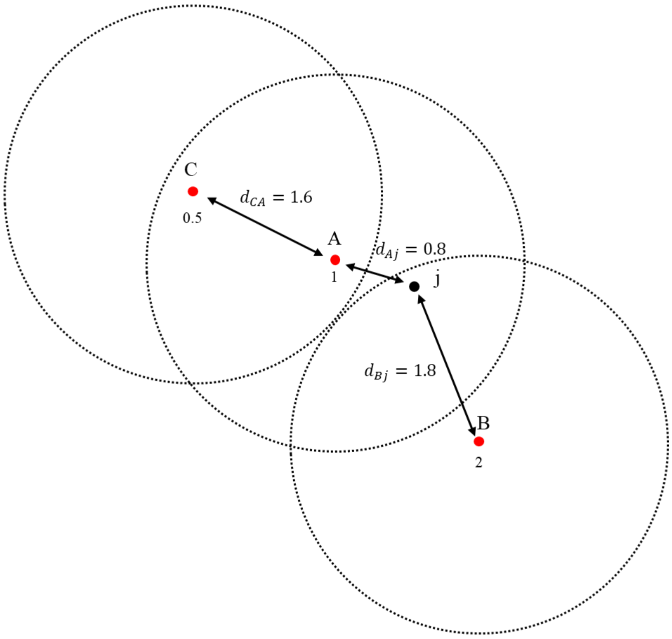
Figure A1 provides an example of this calculation. In Figure A1, there are three property transactions at the same time t, denoted as Points A, B, and C. The numbers below the points (i.e. 1, 2, and 0.5) are the deflated transaction prices in million £. The circles around Points A, B, and C represent 2 km radius. Point j is the point at which we need to estimate its local property market heat. Since the distance between point C and j is more than 2 km, point C doesn't exert any heat on point j. Thus, only Point A (with a distance of d_{Aj}=0.8 km) and Point B (with a distance of d_{Bj}=1.8 km) generate disease pressure on Point j. The property market heat of Point j is then:

$$U_{j,t} = Price_{A,t} * \frac{3}{4} * \left(1 - \left(\frac{d_{A,j,t}}{2}\right)^2\right) + Price_{B,t} * \frac{3}{4} * \left(1 - \left(\frac{d_{B,j,t}}{2}\right)^2\right)$$
$$= 1 * \frac{3}{4} * \left(1 - \left(\frac{0.8}{2}\right)^2\right) + 2 * \frac{3}{4} * \left(1 - \left(\frac{1.8}{2}\right)^2\right) = 0.63 + 0.285 = 0.915$$

Another point that needs to be noticed is, the local property market heat at Point A (denotes as $U_{a,t}$) is not equals to $Price_{A,t}$=1, it also needs to be calculated by the method above. Specifically, it is:

$$U_{a,t} = Price_{A,t} * \frac{3}{4} * \left(1 - \left(\frac{d_{A,a,t}}{2}\right)^2\right) + Price_{C,t} * \frac{3}{4} * \left(1 - \left(\frac{d_{C,a,t}}{2}\right)^2\right)$$
$$= 1 * \frac{3}{4} * \left(1 - \left(\frac{0}{100}\right)^2\right) + 0.5 * \frac{3}{4} * \left(1 - \left(\frac{1.6}{2}\right)^2\right) = 0.75 + 0.135 = 0.885$$

Figure A1: Example of KDE



The reason we use Epanechnikov function is that it allows the property market heat that a transaction exerts to decrease as distance increases, and the decreasing rate is faster as distance increases. It means, in the Equation A1, $K'(u) < 0, K''(u) < 0$. Also, this property market heat will become 0 at the edge of the settled radius. Figure A2 is the function graph of Equation A1, it can better show the trend.

Figure A2: Graph of Epanechnikov function

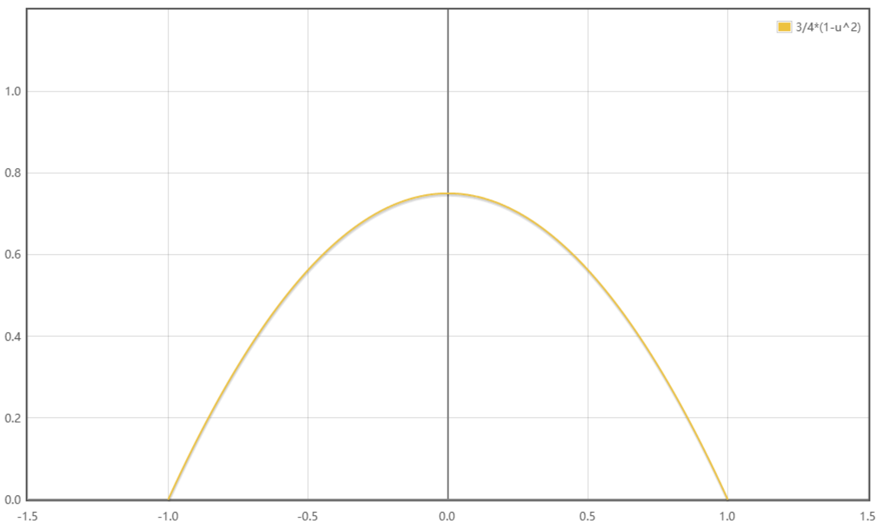
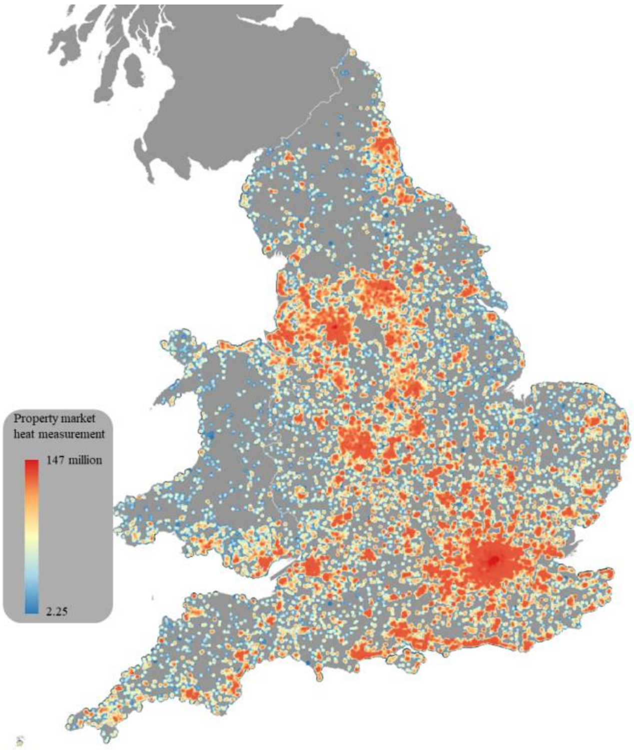


Figure A3 shows a heatmap example generated by KDE with property transactions in Dec. 2018. Finally, we match the geocode of herds with the property market heatmap and assign the localized property market "heat" to herds as an alternative proxy of urbanization level.

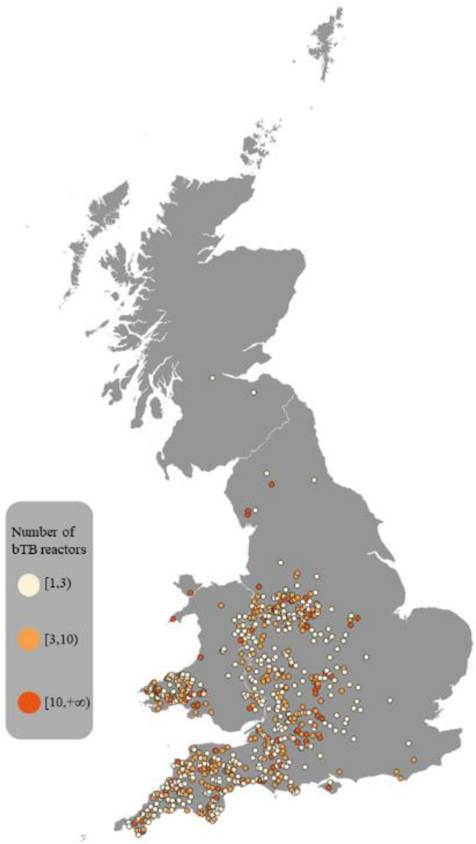
Figure A3: Property transactions heatmap example in Dec. 2018



Appendix B. Using Kernel Density Estimator to generate local bTB disease pressure

We employ the Kernel Density Estimator (KDE) in QGIS to generate the heatmap of bTB prevalence. First, we use monthly bTB-positive animal reactors to generate the heatmap. For example, in Dec. 2018, about 8.6 million head of cattle lived in Britain, with a heavy concentration in Western England, Wales, and Eastern Scotland. About 0.76 million cattle received skin tests, about 20,000 had blood tests, and finally, 3551 cattle had positive bTB results. Figure B1 shows their spatial distribution. Thus, these bTB-positive herds will generate disease pressure on others.

Figure B1: Spatial distribution of bTB reactors in Dec. 2018



We then set the radius of KDE as 100 kilometers, which means every herd with positive bTB reactors would exert disease pressure on other herds within 100 kilometers. We set the Kernel Shape decided by Epanechnikov function. We set the weight of every bTB-contaminated herd as its number of positive cattle reactors, thus herds with more positive bTB cattle will exert more disease pressure on other herds.

The Epanechnikov function is shown below:

$$K(u) = \frac{3}{4}(1 - u^2), u \in [-1,1] \quad \text{(B1)}$$

By employing the Epanechnikov function into our disease pressure context, it can be rewritten as:

$$P_{ij} = KWI\frac{3}{4}\left(1 - \left(\frac{d_{ij}}{radius}\right)^2\right), |d_{ij}| \leq radius \quad \text{(B2)}$$

Where P_{ij} is the disease pressure that the herd i generates on point j, K is a constant, W is the weight, I represents intensity. Notice that in QGIS, it has an option to set "weight", which is different from our W in the function. The "weight" in QGIS can be considered as the product of $K * W * I$. d_{ij} is the distance between the herd i and point j. $radius$ is the farthest distance that a bTB-positive herd can exert disease pressure. By inputting our settings, the function is:

$$P_{i,j,t} = Num\_Reactors_{i,t} * \frac{3}{4} * \left(1 - \left(\frac{d_{i,j,t}}{100}\right)^2\right), d_{i,j,t} \leq 100 \quad \text{(B3)}$$

Where $Num\_Reactors_{i,t}$ is the number of positive animal reactors in a herd i at time t.

Thus, for a specific point j, the estimated disease pressure is:

$$D_{j,t} = \sum_{i=1}^{m} Num\_Reactors_{i,t} * \frac{3}{4} * \left(1 - \left(\frac{d_{i,j,t}}{100}\right)^2\right) \quad \text{(B4)}$$

Where m is the total number of herds with positive bTB reactors that are within 100 kilometers of a point j.

Figure B2 provides an example of this calculation. In Figure B2, there are three bTB-positive herds at the same time t, denoted as Points A, B, and C. The numbers below the points (i.e. 10, 100, and 30) are the number of positive animals. The circles around Points A, B, and C represent a 100 km radius. Point j is the point at which we need to estimate its local disease pressure. Since the distance between point C and j is more than 100 km, point C doesn't exert any pressure on point j. Thus, only Point A (with a distance of d_{Aj}=40 km) and Point B (with a distance of d_{Bj}=90 km) generate disease pressure on Point j. The disease pressure of Point j is then:

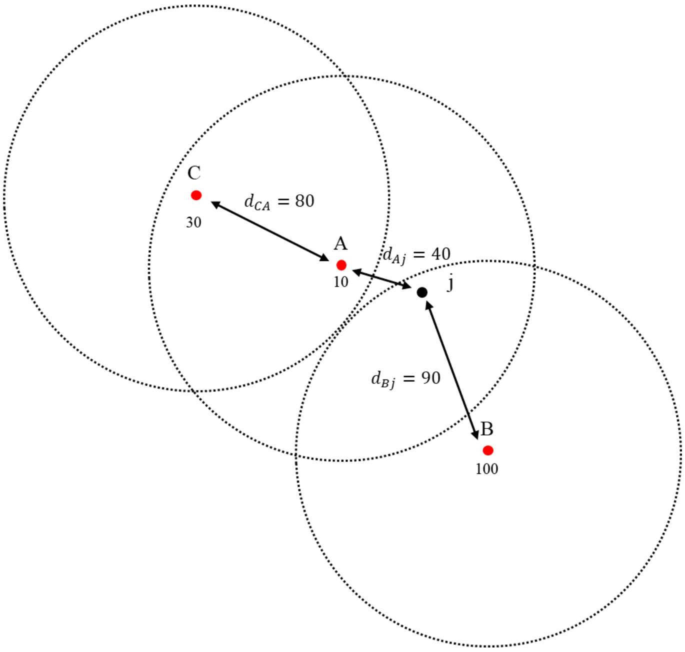
$$D_{j,t} = Num\_Reactors_{A,t} * \frac{3}{4} * \left(1 - \left(\frac{d_{A,j,t}}{100}\right)^2\right) + Num_{Reactors_{B,t}} * \frac{3}{4} * \left(1 - \left(\frac{d_{B,j,t}}{100}\right)^2\right)$$

$$= 10 * \frac{3}{4} * \left(1 - \left(\frac{40}{100}\right)^2\right) + 100 * \frac{3}{4} * \left(1 - \left(\frac{90}{100}\right)^2\right) = 6.3 + 14.25 = 20.55$$

Another point that needs to be noticed is the local disease pressure of Point A (denoted as $D_{a,t}$) is not equal to $Num\_Reactors_{A,t}$=10, it also needs to be calculated by the method above. Specifically, it is:

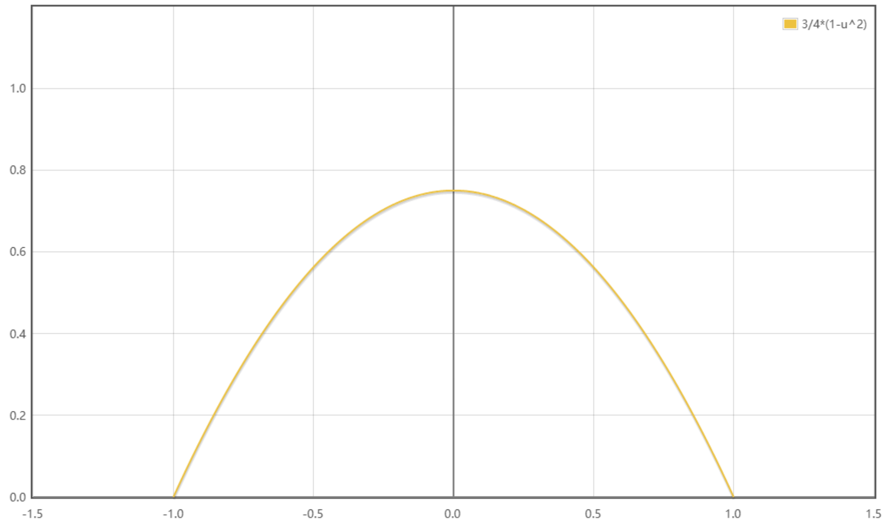
$$D_{a,t} = Num\_Reactors_{A,t} * \frac{3}{4} * \left(1 - \left(\frac{d_{A,a,t}}{100}\right)^2\right) + Num_{Reactors_{C,t}} * \frac{3}{4} * \left(1 - \left(\frac{d_{C,a,t}}{100}\right)^2\right)$$
$$= 10 * \frac{3}{4} * \left(1 - \left(\frac{0}{100}\right)^2\right) + 30 * \frac{3}{4} * \left(1 - \left(\frac{80}{100}\right)^2\right) = 7.5 + 8.1 = 15.6$$

Figure B2: Example of KDE



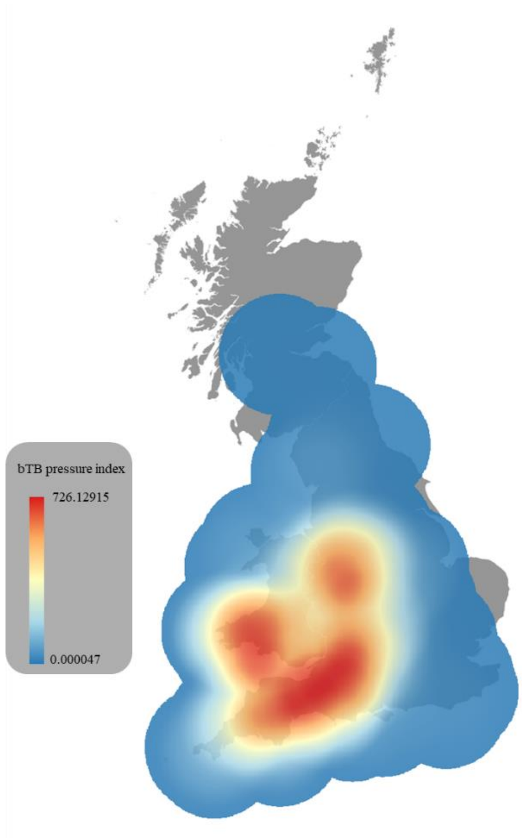
The reason we use Epanechnikov function is that it allows the disease pressure that a herd exerts to decrease as distance increases, and the decreasing rate is faster as distance increases. It means, in Equation B1, $K'(u) < 0, K''(u) < 0$. Also, this disease pressure will become 0 at the edge of the settled radius. Figure A3 is the function graph of Equation B1, which can better show the trend.

Figure B3: Graph of Epanechnikov function



Finally, Figure B4 shows a heatmap example generated by KDE with bTB-positive reactors in Dec. 2018.

Figure B4: bTB heatmap example in Dec. 2018



Appendix C. More Robustness Checks

Appendix C1. Specifications with different fixed effect settings

Although in our baseline approaches we apply two-way fixed effects to control unobserved time-invariant and herd-invariant factors, we provide results without fixed effects or with only one-way fixed effects and help test the robustness of our findings. Another reason for this robustness check is that the two-way fixed effects approach may result in biased estimations under some circumstances (Sun and Shapiro, 2022; De Chaisemartin and d'Haultfoeuille, 2020).

Table C1 reports the results for robustness checks by changing the fixed effects settings and using the localized nightlight measurement as the proxy for urbanization. Table C2 reports the results of using the localized property market measurement as the proxy. Table C3 reports the results of using the regional nightlight measurement as the proxy. Table C4 reports the results of using the regional property market measurement as the proxy.

In Table C1, Columns (1) to (3) use the specifications with bTB_Dummy_{it} to test the relationship between bTB presence with localized urbanization. Columns (4) to (6) use the specifications with bTB_Ratio_{it} to test the relationship between bTB intensity with localized urbanization. And Column (7) to (8) use the specifications with bTB_Number_{it} to test the relationship between bTB prevalence with localized urbanization. Columns (1), (4), and (7) are specifications without any fixed effects. Columns (2), (5), and (8) are specifications only with herd-level fixed effects. Columns (3), (6), and (9) are specifications only with year-month level fixed effects. We can see that all the estimated coefficients of localized nightlight measurements, if statistically significant, are negative. These results also suggest that localized urbanization levels can alleviate the bTB situations, which are highly consistent with our baseline results. And the magnitudes of these estimations are larger than those of our baseline approaches.

Similar to the specifications in Table C2, but applying the regional nightlight measurement as the independent variable, Table C2 shows the results between regional urbanization and bTB situations with one-way fixed effect or without any fixed effects. These results are not always consistent with our baseline results. In our baseline approach, we find that the number of bTB cases is positively related to regional nightlight measurement. However, as reported in Table C2, if we only hold one-way fixed effects or no fixed effects, we generated negative relationships. And notice that these robustness checks are not generating consistent results among themselves. For example, if we test the relationship with bTB presence (i.e. bTB_Dummy_{it}) without fixed effect or with only year-month fixed effect, we will generate statistically significant negative results, on the other hand, if we only keep herd level fixed effect, it will generate positive results. These inconsistencies suggest that both herd-invariant and time-invariant unobserved factors have significant impacts on the findings, thus we believe our baseline approach with two-way fixed effects could better control these factors and generate more reliable results.

Table C3 reports the results for checking the relationship between bTB situations and localized property market measurement with one-way fixed effects or without fixed effects. We can see that almost all the estimated coefficients of localized property market measurements, if statistically significant, are negative. The only positive result is the one testing bTB presence (i.e. bTB_Dummy_{it}) with only year-month fixed effect, which can't control for herd-level unobserved factors. Despite this one different result, most robustness checks here also suggest that localized urbanization level can alleviate the bTB situations, which are highly consistent with our baseline results.

Table C4 reports the results for testing the relationship between bTB situations and regional property market measurement with one-way fixed effects or without fixed effects. Like the results of using regional nightlight, these results are inconsistent among themselves.

References

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De Chaisemartin, C., & d'Haultfoeuille, X. (2020). Two-way fixed effects estimators with heterogeneous treatment effects. American Economic Review, 110(9), 2964-2996.

Table C1: Localized nightlight and bTB disease with one-way fixed effect or without fixed effects

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	bTB_Dummy_{it}	bTB_Dummy_{it}	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Ratio_{it}	bTB_Ratio_{it}	bTB_Number_{it}	bTB_Number_{it}	bTB_Number_{it}
$Urbanization\_Nightlight_{it}$	-0.000126***	0.000008	-0.000131***	-0.000762***	0.000024	-0.000768***	-0.000517***	-0.000217**	-0.000501***
	(0.000014)	(0.000019)	(0.000014)	(0.000117)	(0.000239)	(0.000115)	(0.000072)	(0.000105)	(0.000073)
$Pressure_{i.t-1}$	0.000014***	0.000007***	0.000014***	0.000054***	0.000005	0.000056***	0.000078***	0.000043***	0.000080***
	(0.000000)	(0.000001)	(0.000000)	(0.000007)	(0.000006)	(0.000007)	(0.000002)	(0.000006)	(0.000002)
$Cattle_{it}$	0.000037***	0.000036***	0.000037***	0.000007	0.000047**	0.000006	0.000184***	0.000511***	0.000183***
	(0.000002)	(0.000002)	(0.000002)	(0.000005)	(0.000020)	(0.000005)	(0.000013)	(0.000047)	(0.000013)
$bTB\_Dummy_{i,t-1}$	0.068230***	-0.004788***	0.068180***	-	-	-	-	-	-
	(0.001512)	(0.001777)	(0.001512)	-	-	-	-	-	-
$Test\_Dummy_{it}$	0.068493***	0.063478***	0.068579***	-	-	-	-	-	-
	(0.000632)	(0.000548)	(0.000633)	-	-	-	-	-	-
$bTB\_Ratio_{i,t-1}$	-	-	-	0.060354***	0.012721	0.060345***	-	-	-
	-	-	-	(0.012331)	(0.010302)	(0.012332)	-	-	-
$Test\_Ratio_{it}$	-	-	-	0.002164***	0.002075***	0.002164***	-	-	-
	-	-	-	(0.000457)	(0.000438)	(0.000457)	-	-	-
$bTB\_Number_{i,t-1}$	-	-	-	-	-	-	0.062282***	0.000110	0.062282***
	-	-	-	-	-	-	(0.006470)	(0.007157)	(0.006470)
$Test\_Number_{it}$	-	-	-	-	-	-	0.001754***	0.001211***	0.001754***
	-	-	-	-	-	-	(0.000073)	(0.000062)	(0.000074)
Constant	-0.007059***	-0.003948***	-0.007119***	-0.002558***	0.007414**	-0.003092***	-0.020895***	-0.037058***	-0.021368***
	(0.000166)	(0.000341)	(0.000166)	(0.000985)	(0.003121)	(0.000932)	(0.001357)	(0.005289)	(0.001366)
Herd fixed effects	No	Yes	No	No	Yes	No	No	Yes	No
Year-month fixed effects	No	No	Yes	No	No	Yes	No	No	Yes
Observations	5024081	5024081	5024081	5024081	5024081	5024081	5024081	5024081	5024081

Cluster standard errors in parentheses. Standard errors are clustered at the herd level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table C2: Regional nightlight and bTB disease with one-way fixed effect or without fixed effects

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	bTB_Dummy_{it}	bTB_Dummy_{it}	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Ratio_{it}	bTB_Ratio_{it}	bTB_Number_{it}	bTB_Number_{it}	bTB_Number_{it}
$Urbanization\_Nightlight_{rt}$	-0.000283***	0.000261***	-0.000305***	-0.001792***	0.000525	-0.001835***	-0.001264***	-0.001234***	-0.001226***
	(0.000029)	(0.000048)	(0.000030)	(0.000240)	(0.000581)	(0.000232)	(0.000162)	(0.000366)	(0.000166)
$Pressure_{i.t-1}$	0.000014***	0.000007***	0.000014***	0.000053***	0.000005	0.000055***	0.000078***	0.000043***	0.000079***
	(0.000000)	(0.000001)	(0.000000)	(0.000007)	(0.000006)	(0.000007)	(0.000002)	(0.000007)	(0.000002)
$Cattle_{it}$	0.000037***	0.000036***	0.000037***	0.000006	0.000047**	0.000006	0.000184***	0.000511***	0.000183***
	(0.000002)	(0.000002)	(0.000002)	(0.000005)	(0.000020)	(0.000005)	(0.000013)	(0.000047)	(0.000013)
$bTB\_Dummy_{i,t-1}$	0.068210***	-0.004789***	0.068156***						
	(0.001512)	(0.001777)	(0.001512)						
$Test\_Dummy_{it}$	0.068479***	0.063481***	0.068565***						
	(0.000632)	(0.000548)	(0.000633)						
$bTB\_Ratio_{i,t-1}$				0.060347***	0.012721	0.060338***			
				(0.012331)	(0.010302)	(0.012332)			
$Test\_Ratio_{it}$				0.002164***	0.002075***	0.002164***			
				(0.000457)	(0.000438)	(0.000457)			
$bTB\_Number_{i,t-1}$							0.062278***	0.000110	0.062278***
							(0.006470)	(0.007157)	(0.006470)
$Test\_Number_{it}$							0.001754***	0.001211***	0.001754***
							(0.000073)	(0.000062)	(0.000074)
Constant	-0.006843***	-0.004262***	-0.006879***	-0.001149	0.006790**	-0.001617	-0.019871***	-0.035793***	-0.020365***
	(0.000170)	(0.000346)	(0.000171)	(0.001118)	(0.003333)	(0.001053)	(0.001376)	(0.005266)	(0.001385)
Herd fixed effects	No	Yes	No	No	Yes	No	No	Yes	No
Year-month fixed effects	No	No	Yes	No	No	Yes	No	No	Yes
Observations	5024081	5024081	5024081	5024081	5024081	5024081	5024081	5024081	5024081

Cluster standard errors in parentheses. Standard errors are clustered at the herd level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table C3: Localized property market measurement and bTB disease with one-way fixed effect or without fixed effects

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	bTB_Dummy_{it}	bTB_Dummy_{it}	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Ratio_{it}	bTB_Ratio_{it}	bTB_Number_{it}	bTB_Number_{it}	bTB_Number_{it}
$Urbanization\_Property_{it}$	0.000016	-0.000079***	0.000049***	-0.000695***	-0.000393**	-0.000529***	0.000090	-0.000155*	0.000121
	(0.000015)	(0.000018)	(0.000015)	(0.000161)	(0.000172)	(0.000149)	(0.000087)	(0.000086)	(0.000088)
$Pressure_{i,t-1}$	0.000012***	0.000011***	0.000013***	0.000058***	0.000032***	0.000061***	0.000065***	0.000051***	0.000067***
	(0.000000)	(0.000000)	(0.000000)	(0.000004)	(0.000005)	(0.000004)	(0.000002)	(0.000003)	(0.000002)
$Cattle_{it}$	0.000045***	0.000038***	0.000045***	0.000013**	0.000034**	0.000013**	0.000267***	0.000413***	0.000267***
	(0.000001)	(0.000002)	(0.000001)	(0.000005)	(0.000014)	(0.000005)	(0.000015)	(0.000029)	(0.000015)
$bTB\_Dummy_{i,t-1}$	0.074845***	0.027578***	0.074755***	-	-	-	-	-	-
	(0.001095)	(0.001241)	(0.001094)	-	-	-	-	-	-
$Test\_Dummy_{it}$	0.074190***	0.071658***	0.074380***	-	-	-	-	-	-
	(0.000558)	(0.000511)	(0.000559)	-	-	-	-	-	-
$bTB\_Ratio_{i,t-1}$	-	-	-	0.071589***	0.040661***	0.071572***	-	-	-
	-	-	-	(0.007161)	(0.006792)	(0.007161)	-	-	-
$Test\_Ratio_{it}$	-	-	-	0.002174***	0.002098***	0.002174***	-	-	-
	-	-	-	(0.000342)	(0.000333)	(0.000342)	-	-	-
$bTB\_Number_{i,t-1}$	-	-	-	-	-	-	0.075022***	0.031678**	0.075019***
	-	-	-	-	-	-	(0.012451)	(0.013379)	(0.012450)
$Test\_Number_{it}$	-	-	-	-	-	-	0.001670***	0.001243***	0.001671***
	-	-	-	-	-	-	(0.000065)	(0.000053)	(0.000065)
Constant	-0.006952***	-0.005138***	-0.007074***	-0.004564***	0.002813	-0.005388***	-0.022344***	-0.024636***	-0.022921***
	(0.000115)	(0.000222)	(0.000116)	(0.000624)	(0.001968)	(0.000606)	(0.001079)	(0.002773)	(0.001090)
Herd fixed effects	No	Yes	No	No	Yes	No	No	Yes	No
Year-month fixed effects	No	No	Yes	No	No	Yes	No	No	Yes
Observations	11813973	11813973	11813973	11813973	11813973	11813973	11813973	11813973	11813973

Cluster standard errors in parentheses. Standard errors are clustered at the herd level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table C4: Regional property market measurement and bTB disease with one-way fixed effect or without fixed effects

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	bTB_Dummy_{it}	bTB_Dummy_{it}	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Ratio_{it}	bTB_Ratio_{it}	bTB_Number_{it}	bTB_Number_{it}	bTB_Number_{it}
$Urbanization\_Property_{rt}$	0.000040***	-0.000169***	0.000099***	-0.001033***	-0.000627***	-0.000746***	0.000073	0.000355**	0.000127
	(0.000015)	(0.000040)	(0.000018)	(0.000239)	(0.000215)	(0.000190)	(0.000095)	(0.000150)	(0.000089)
$Pressure_{i,t-1}$	0.000012***	0.000011***	0.000013***	0.000058***	0.000032***	0.000061***	0.000065***	0.000051***	0.000067***
	(0.000000)	(0.000000)	(0.000000)	(0.000004)	(0.000005)	(0.000004)	(0.000002)	(0.000003)	(0.000002)
$Cattle_{it}$	0.000045***	0.000038***	0.000045***	0.000013**	0.000034**	0.000013**	0.000267***	0.000414***	0.000267***
	(0.000001)	(0.000002)	(0.000001)	(0.000005)	(0.000014)	(0.000005)	(0.000015)	(0.000029)	(0.000015)
$bTB\_Dummy_{i,t-1}$	0.074845***	0.027578***	0.074755***	-	-	-	-	-	-
	(0.001095)	(0.001241)	(0.001094)	-	-	-	-	-	-
$Test\_Dummy_{it}$	0.074191***	0.071658***	0.074380***	-	-	-	-	-	-
	(0.000558)	(0.000511)	(0.000559)	-	-	-	-	-	-
$bTB\_Ratio_{i,t-1}$	-	-	-	0.071588***	0.040661***	0.071572***	-	-	-
	-	-	-	(0.007161)	(0.006792)	(0.007161)	-	-	-
$Test\_Ratio_{it}$	-	-	-	0.002174***	0.002098***	0.002174***	-	-	-
	-	-	-	(0.000342)	(0.000333)	(0.000342)	-	-	-
$bTB\_Number_{i,t-1}$	-	-	-	-	-	-	0.075022***	0.031678**	0.075019***
	-	-	-	-	-	-	(0.012451)	(0.013379)	(0.012450)
$Test\_Number_{it}$	-	-	-	-	-	-	0.001670***	0.001242***	0.001671***
	-	-	-	-	-	-	(0.000065)	(0.000053)	(0.000065)
Constant	-0.006964***	-0.005109***	-0.007097***	-0.004414***	0.002888	-0.005292***	-0.022334***	-0.024801***	-0.022921***
	(0.000114)	(0.000222)	(0.000116)	(0.000632)	(0.001967)	(0.000611)	(0.001070)	(0.002774)	(0.001081)
Herd fixed effects	No	Yes	No	No	Yes	No	No	Yes	No
Year-month fixed effects	No	No	Yes	No	No	Yes	No	No	Yes
Observations	11813973	11813973	11813973	11813973	11813973	11813973	11813973	11813973	11813973

Cluster standard errors in parentheses. Standard errors are clustered at the herd level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Appendix C2. Specifications with the interaction terms

In this section, we conduct a battery of robustness checks by adding the interaction terms between urbanization measurements and local bTB pressure. With this added interaction, we are able to see if the impacts of urbanization on bTB disease situations are also affected by bTB pressures. For example, maybe higher urban areas are more powerful in controlling bTB prevalence when the nearby bTB pressure is low, as it can denote more resources in wild animal control. But urban areas may be less effective in controlling when the nearby bTB pressure is higher because there are more frequent livestock trades that can bring in the disease.

Table C5 reports the results of testing the relationships with localized urbanization levels. Columns (1) to (3) use nightlight measurements, and Columns (4) to (6) use property market measurements. The results indicate that the effects of localized urbanization on bTB disease situations are affected by nearby bTB pressures. Specifically, notice that the estimated coefficient of the interaction terms in Column (1), (3), (4), and (6) are all significantly negative, which indicates that as nearby bTB pressure increases, the urban areas will get worse in controlling bTB presence and prevalence (i.e. bTB_Dummy_{it} and bTB_Number_{it}). However, we don't observe similar effects with bTB intensity (i.e. bTB_Ratio_{it}). We provide the estimated marginal effects of urbanization measurements on bTB situations at the average bTB pressure levels at the bottom of the table. We can see that the marginal effects are consistent with our baseline findings that localized urbanization can generally alleviate the bTB situations.

Table C6 reports the results of testing the impacts of regional urbanization levels. Columns (1) to (3) use nightlight measurements, and Columns (4) to (6) use property market measurements. Specifically, when looking at the estimated coefficient of the interaction terms in Columns (1) and (3) with the nightlight measurements, we observe similar conclusions that as nearby bTB pressure increases, the urban areas will get worse in controlling bTB presence and prevalence. However, we don't observe similar effects with the rest specifications. We also provide the estimated marginal effects of urbanization measurements on bTB situations at the average bTB pressure levels at the bottom of the table. Nevertheless, most of the marginal effects are not statistically significant, which contributes little as a robustness check.

Table C5: Localized urbanization measurements and bTB situations with interaction terms

	(1)	(2)	(3)	(4)	(5)	(6)
	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Number_{it}	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Number_{it}
$Urbanization\_Nightlight_{it}$	0.000008	-0.000083	0.000368***	-	-	-
	(0.000018)	(0.000172)	(0.000116)	-	-	-
$Urbanization\_Nightlight_{it}$	-0.000000**	0.000001	-0.000003***	-	-	-
$* Pressure_{i.t-1}$	(0.000000)	(0.000001)	(0.000001)	-	-	-
$Urbanization\_Property_{it}$	-	-	-	0.000044***	0.000158	0.000278***
	-	-	-	(0.000014)	(0.000128)	(0.000084)
$Urbanization\_Property_{it}$	-	-	-	-0.000000**	-0.000001	-0.000002***
$* Pressure_{i.t-1}$	-	-	-	(0.000000)	(0.000001)	(0.000001)
$Pressure_{i.t-1}$	0.000008***	0.000011	0.000044***	0.000013***	0.000046***	0.000061***
	(0.000001)	(0.000007)	(0.000007)	(0.000000)	(0.000006)	(0.000004)
$Cattle_{it}$	0.000036***	0.000047**	0.000511***	0.000037***	0.000033**	0.000413***
	(0.000002)	(0.000020)	(0.000047)	(0.000002)	(0.000014)	(0.000029)
$bTB\_Dummy_{i,t-1}$	-0.004797***	-	-	0.027520***		
	(0.001776)	-	-	(0.001241)		
$Test\_Dummy_{it}$	0.063616***	-	-	0.071899***		
	(0.000549)	-	-	(0.000512)		
$bTB\_Ratio_{i,t-1}$	-	0.012718	-		0.040646***	
	-	(0.010303)	-		(0.006792)	
$Test\_Ratio_{it}$	-	0.002075***	-		0.002098***	
	-	(0.000438)	-		(0.000333)	
$bTB\_Number_{i,t-1}$	-	-	0.000107			0.031670**
	-	-	(0.007157)			(0.013378)
$Test\_Number_{it}$	-	-	0.001211***			0.001243***
	-	-	(0.000062)			(0.000053)
Constant	-0.004081***	0.005881*	-0.037425***	-0.005875***	-0.001402	-0.027528***
	(0.000354)	(0.003212)	(0.005348)	(0.000234)	(0.002162)	(0.002825)
Marginal effects of	-0.000072**	0.000074	-0.000301	-0.000031	-0.000128	-0.000440***
urbanization measurements at average $Pressure_{i.t-1}$	(0.000032)	(0.000373)	(0.000186)	(0.000025)	(0.000232)	(0.000147)
Herd fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year-month fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	5024081	5024081	5024081	11813973	11813973	11813973

Cluster standard errors in parentheses. Standard errors are clustered at the herd level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table C6: Regional urbanization measurements and bTB situations with interaction terms

	(1)	(2)	(3)	(4)	(5)	(6)
	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Number_{it}	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Number_{it}
$Urbanization\_Nightlight_{rt}$	0.000014	0.000359	0.001581***	-	-	-
	(0.000067)	(0.000574)	(0.000490)	-	-	-
$Urbanization\_Nightlight_{rt}$	-0.000001**	0.000001	-0.000008***	-	-	-
$* Pressure_{i.t-1}$	(0.000000)	(0.000003)	(0.000003)	-	-	-
$Urbanization\_Property_{rt}$	-	-	-	0.000042*	0.000640***	0.000188
	-	-	-	(0.000024)	(0.000237)	(0.000154)
$Urbanization\_Property_{rt}$	-	-	-	-0.000000	-0.000003	0.000001
$* Pressure_{i.t-1}$	-	-	-	(0.000000)	(0.000002)	(0.000002)
$Pressure_{i.t-1}$	0.000008***	0.000010	0.000049***	0.000013***	0.000047***	0.000060***
	(0.000001)	(0.000008)	(0.000008)	(0.000001)	(0.000006)	(0.000004)
$Cattle_{it}$	0.000036***	0.000047**	0.000511***	0.000037***	0.000033**	0.000413***
	(0.000002)	(0.000020)	(0.000047)	(0.000002)	(0.000014)	(0.000029)
$bTB\_Dummy_{i,t-1}$	-0.004796***			0.027520***		
	(0.001776)			(0.001241)		
$Test\_Dummy_{it}$	0.063616***			0.071899***		
	(0.000549)			(0.000512)		
$bTB\_Ratio_{i,t-1}$		0.012718			0.040646***	
		(0.010302)			(0.006792)	
$Test\_Ratio_{it}$		0.002075***			0.002098***	
		(0.000438)			(0.000333)	
$bTB\_Number_{i,t-1}$			0.000106			0.031671**
			(0.007157)			(0.013378)
$Test\_Number_{it}$			0.001211***			0.001243***
			(0.000062)			(0.000053)
Constant	-0.004069***	0.005349*	-0.038564***	-0.005875***	-0.001564	-0.027496***
	(0.000362)	(0.003203)	(0.005321)	(0.000234)	(0.002161)	(0.002826)
Marginal effects of urbanization measurements at average $Pressure_{i.t-1}$	-0.000175*	0.000605	-0.000587	0.000014	-0.000177	0.000601
	(0.000094)	(0.000925)	(0.000821)	(0.000059)	(0.000589)	(0.000419)
Herd fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year-month fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	5024081	5024081	5024081	11813973	11813973	11813973

Cluster standard errors in parentheses. Standard errors are clustered at the herd level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Appendix C3. Specifications with dynamic variables in the regressions.

In this section, we provide the robustness checks with up to 12 months' lags of urbanization measurements and nearby bTB pressures. This approach can check if the urban expansions have lagged effects on bTB situations.

Table C7 reports the regression results using localized urbanization measurements. Columns (1) to (3) use nightlight measurements proxy for localized urbanization, and Columns (4) to (6) apply property market measurements as the proxy. In the table, we also report the linear combinations of estimated coefficients for urbanization measurements (i.e. $\sum_{t-12}^{t} Estimator\ of\ Urbanization\_Proxy_{it}$), which represent the aggregated estimated effects of current and past 12 months' urbanization level on bTB situations. From Column (2), we can see that localized nightlight increases can statistically significantly decrease herds' bTB intensity. Although we don't observe a significant negative estimator for localized nightlight on bTB presence, we can see that the estimators are almost significant (-0.000160 is the estimated coefficient and 0.000098 is the clustered standard error). These results well support our baseline findings.

Table C8 shows the results using regional urbanization measurements. Linear combinations of estimated coefficients for urbanization measurements (i.e. $\sum_{t-12}^{t} Estimator\ of\ Urbanization\_Proxy_{rt}$) are also provided at the bottom of the table. Columns (1) to (3) use the nightlight measurements proxy for localized urbanization. When using the nightlight proxy, we observe a statistically significant negative relationship between past 12 months' regional urbanization and current bTB intensity (see Column (2) of Table C8), but we don't observe significant impacts on bTB presence or prevalence. Columns (4) to (6) apply the property market measurement as the proxy. We only observe a significant positive relationship between aggregated regional property market heat measurements and bTB intensity (see Column (5) of Table C8), which is consistent with our baseline results but inconsistent with the ones using nightlight as the proxy in this section (see Column (2) of Table C8). For the estimated impacts on bTB presence and cases, although not significant, are still positive. These results, especially those using the property market index, further support our baseline findings that regional urbanization will aggravate bTB situations.

Table C7: Localized urbanization measurements and bTB situations with dynamic variables

	Nightlight			Property		
	(1)	(2)	(3)	(4)	(5)	(6)
	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Number_{it}	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Number_{it}
$Urbanization\_Proxy_{it}$	-0.000037	-0.000121	-0.000070	-0.000026	-0.000093	-0.000243***
	(0.000026)	(0.000264)	(0.000135)	(0.000017)	(0.000144)	(0.000092)
$Urbanization\_Proxy_{i,t-1}$	-0.000006	-0.000238	0.000076	0.000078***	0.000440	0.000236**
	(0.000027)	(0.000257)	(0.000135)	(0.000026)	(0.000300)	(0.000104)
$Urbanization\_Proxy_{i,t-2}$	0.000011	-0.000346*	0.000070	0.000010	-0.000119	-0.000091
	(0.000025)	(0.000190)	(0.000145)	(0.000017)	(0.000132)	(0.000108)
$Urbanization\_Proxy_{i,t-3}$	-0.000011	-0.000309	-0.000080	-0.000020	-0.000197	-0.000219**
	(0.000023)	(0.000203)	(0.000140)	(0.000020)	(0.000133)	(0.000094)

$Urbanization\_Proxy_{i,t-4}$	-0.000013	-0.000266	0.000086	-0.000008	0.000084	0.000028
	(0.000026)	(0.000191)	(0.000153)	(0.000024)	(0.000177)	(0.000119)
$Urbanization\_Proxy_{i,t-5}$	-0.000025	-0.000422**	-0.000477***	0.000014	-0.000092	0.000069
	(0.000025)	(0.000188)	(0.000170)	(0.000023)	(0.000122)	(0.000124)
$Urbanization\_Proxy_{i,t-6}$	-0.000053**	-0.000059	-0.000269*	-0.000009	0.000066	-0.000073
	(0.000026)	(0.000194)	(0.000145)	(0.000019)	(0.000143)	(0.000116)
$Urbanization\_Proxy_{i,t-7}$	-0.000026	-0.000196	0.000003	-0.000007	-0.000038	-0.000019
	(0.000026)	(0.000161)	(0.000133)	(0.000022)	(0.000139)	(0.000120)
$Urbanization\_Proxy_{i,t-8}$	-0.000035	-0.000016	-0.000040	0.000014	0.000180	0.000267
	(0.000024)	(0.000166)	(0.000178)	(0.000024)	(0.000213)	(0.000210)
$Urbanization\_Proxy_{i,t-9}$	0.000027	-0.000078	0.000132	-0.000008	-0.000120	-0.000175
	(0.000029)	(0.000206)	(0.000205)	(0.000019)	(0.000127)	(0.000115)
$Urbanization\_Proxy_{i,t-10}$	0.000044*	0.000046	0.000034	-0.000011	-0.000014	-0.000032
	(0.000026)	(0.000172)	(0.000173)	(0.000018)	(0.000134)	(0.000110)
$Urbanization\_Proxy_{i,t-11}$	-0.000037*	-0.000257	-0.000092	-0.000021	-0.000076	-0.000148
	(0.000022)	(0.000174)	(0.000152)	(0.000019)	(0.000151)	(0.000111)
$Urbanization\_Proxy_{i,t-12}$	0.000003	-0.000055	0.000058	0.000004	0.000081	-0.000002
	(0.000027)	(0.000249)	(0.000157)	(0.000021)	(0.000161)	(0.000111)
$Pressure_{i.t-1}$	0.000004***	0.000001	0.000023**	0.000006***	0.000012**	0.000022***
	(0.000001)	(0.000009)	(0.000009)	(0.000001)	(0.000006)	(0.000004)
$Pressure_{i.t-2}$	0.000004***	0.000012	0.000027**	0.000006***	0.000023***	0.000032***
	(0.000001)	(0.000009)	(0.000011)	(0.000001)	(0.000006)	(0.000005)
$Pressure_{i.t-3}$	0.000006***	0.000024**	0.000023**	0.000007***	0.000029***	0.000033***
	(0.000001)	(0.000010)	(0.000009)	(0.000001)	(0.000006)	(0.000005)
$Pressure_{i.t-4}$	0.000001	-0.000006	-0.000003	-0.000001	0.000001	-0.000007*
	(0.000001)	(0.000009)	(0.000009)	(0.000001)	(0.000006)	(0.000004)
$Pressure_{i.t-5}$	-0.000001	-0.000013	-0.000009	-0.000001	-0.000007	-0.000006
	(0.000001)	(0.000009)	(0.000009)	(0.000001)	(0.000006)	(0.000005)
$Pressure_{i.t-6}$	-0.000000	-0.000011	-0.000004	0.000000	-0.000001	-0.000001
	(0.000001)	(0.000009)	(0.000010)	(0.000001)	(0.000006)	(0.000005)
$Pressure_{i.t-7}$	-0.000001	-0.000010	-0.000004	0.000000	0.000002	-0.000000
	(0.000001)	(0.000009)	(0.000009)	(0.000001)	(0.000006)	(0.000004)
$Pressure_{i.t-8}$	-0.000000	0.000002	0.000022**	0.000000	0.000001	0.000011**
	(0.000001)	(0.000008)	(0.000009)	(0.000001)	(0.000006)	(0.000004)
$Pressure_{i.t-9}$	-0.000001	0.000013	-0.000012	0.000000	0.000009*	0.000004
	(0.000001)	(0.000009)	(0.000009)	(0.000001)	(0.000005)	(0.000004)
$Pressure_{i.t-10}$	-0.000001	0.000006	0.000006	0.000001*	0.000005	0.000004
	(0.000001)	(0.000010)	(0.000009)	(0.000001)	(0.000006)	(0.000004)
$Pressure_{i.t-11}$	-0.000003***	-0.000006	-0.000002	-0.000001**	0.000002	-0.000002
	(0.000001)	(0.000009)	(0.000010)	(0.000001)	(0.000005)	(0.000004)
$Pressure_{i.t-12}$	0.000005***	0.000014	0.000024***	0.000005***	0.000011*	0.000018***
	(0.000001)	(0.000009)	(0.000009)	(0.000001)	(0.000006)	(0.000004)
$Cattle_{it}$	0.000046***	0.000062***	0.000722***	0.000038***	0.000029*	0.000417***

	(0.000004)	(0.000020)	(0.000075)	(0.000002)	(0.000016)	(0.000031)
$bTB\_Dummy_{i,t-1}$	-0.013755***			0.023026***		
	(0.001924)			(0.001292)		
$Test\_Dummy_{it}$	0.067334***			0.070490***		
	(0.000608)			(0.000515)		
$bTB\_Ratio_{i,t-1}$		0.007103			0.035663***	
		(0.010316)			(0.007191)	
$Test\_Ratio_{it}$		0.003047***			0.002114***	
		(0.000603)			(0.000355)	
$bTB\_Number_{i,t-1}$			-0.006745			0.028262*
			(0.007984)			(0.014767)
$Test\_Number_{it}$			0.001210***			0.001262***
			(0.000071)			(0.000049)
Constant	-0.006020***	-0.001385	-0.063798***	-0.008850***	-0.013977***	-0.042034***
	(0.000962)	(0.008123)	(0.012473)	(0.000352)	(0.003429)	(0.003481)
Linear combinations of estimated coefficients for urbanization measurements	-0.000160	-0.002316***	-0.000569	0.000008	0.000102	-0.000401*
	(0.000098)	(0.000757)	(0.000603)	(0.000029)	(0.000292)	(0.000231)
Herd fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year-month fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3273261	3273261	3273261	10821960	10821960	10821960

Cluster standard errors in parentheses. Standard errors are clustered at the herd level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table C8: Regional urbanization measurements and bTB situations with dynamic variables

	Nightlight			Property		
	(1)	(2)	(3)	(4)	(5)	(6)
	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Number_{it}	bTB_Dummy_{it}	bTB_Ratio_{it}	bTB_Number_{it}
$Urbanization\_Proxy_{rt}$	-0.000054	0.000414	0.000274	-0.000048**	-0.000000	-0.000125
	(0.000085)	(0.000727)	(0.000572)	(0.000022)	(0.000147)	(0.000131)
$Urbanization\_Proxy_{r,t-1}$	-0.000089	-0.000508	0.000657	0.000054**	0.000259	0.000150
	(0.000065)	(0.000693)	(0.000488)	(0.000023)	(0.000175)	(0.000117)
$Urbanization\_Proxy_{r,t-2}$	0.000035	-0.000454	-0.000455	0.000025	-0.000025	-0.000009
	(0.000065)	(0.000543)	(0.000448)	(0.000022)	(0.000134)	(0.000123)
$Urbanization\_Proxy_{r,t-3}$	0.000292***	0.000399	0.000577	0.000005	-0.000035	-0.000210
	(0.000065)	(0.000636)	(0.000510)	(0.000023)	(0.000184)	(0.000128)
$Urbanization\_Proxy_{r,t-4}$	0.000172**	0.000018	-0.000770	-0.000007	-0.000100	0.000132
	(0.000069)	(0.000524)	(0.000612)	(0.000020)	(0.000178)	(0.000132)
$Urbanization\_Proxy_{r,t-5}$	-0.000143**	0.000063	-0.000691	0.000001	0.000043	0.000101
	(0.000071)	(0.000502)	(0.000817)	(0.000021)	(0.000153)	(0.000136)
$Urbanization\_Proxy_{r,t-6}$	-0.000500***	-0.001660***	-0.001389***	0.000005	0.000042	0.000147
	(0.000067)	(0.000637)	(0.000523)	(0.000024)	(0.000202)	(0.000138)

$Urbanization\_Proxy_{r,t-7}$	-0.000012	0.000040	0.000617	-0.000032	-0.000069	-0.000083
	(0.000071)	(0.000544)	(0.000489)	(0.000024)	(0.000195)	(0.000144)
$Urbanization\_Proxy_{r,t-8}$	-0.000228***	-0.001005	-0.000769	-0.000030	0.000276	0.000029
	(0.000071)	(0.000647)	(0.000509)	(0.000023)	(0.000206)	(0.000144)
$Urbanization\_Proxy_{r,t-9}$	-0.000081	0.000264	-0.000812	-0.000001	-0.000033	-0.000028
	(0.000070)	(0.000581)	(0.000648)	(0.000022)	(0.000184)	(0.000139)
$Urbanization\_Proxy_{r,t-10}$	0.000369***	0.000665	0.002007***	0.000093***	0.000327	0.000178
	(0.000070)	(0.000636)	(0.000502)	(0.000030)	(0.000227)	(0.000158)
$Urbanization\_Proxy_{r,t-11}$	-0.000251***	-0.002283***	-0.001328***	-0.000006	-0.000230	-0.000077
	(0.000070)	(0.000695)	(0.000513)	(0.000023)	(0.000178)	(0.000172)
$Urbanization\_Proxy_{r,t-12}$	0.000156*	-0.000007	0.000916	-0.000027	-0.000005	0.000052
	(0.000083)	(0.000723)	(0.000573)	(0.000023)	(0.000168)	(0.000197)
$Pressure_{i.t-1}$	0.000004***	0.000001	0.000022**	0.000006***	0.000012**	0.000022***
	(0.000001)	(0.000009)	(0.000009)	(0.000001)	(0.000006)	(0.000004)
$Pressure_{i.t-2}$	0.000004***	0.000012	0.000027**	0.000006***	0.000023***	0.000032***
	(0.000001)	(0.000009)	(0.000011)	(0.000001)	(0.000006)	(0.000005)
$Pressure_{i.t-3}$	0.000006***	0.000023**	0.000021**	0.000007***	0.000029***	0.000033***
	(0.000001)	(0.000010)	(0.000009)	(0.000001)	(0.000006)	(0.000005)
$Pressure_{i.t-4}$	0.000001	-0.000005	-0.000003	-0.000001	0.000001	-0.000008*
	(0.000001)	(0.000009)	(0.000009)	(0.000001)	(0.000006)	(0.000004)
$Pressure_{i.t-5}$	-0.000001	-0.000013	-0.000009	-0.000001	-0.000007	-0.000006
	(0.000001)	(0.000009)	(0.000009)	(0.000001)	(0.000006)	(0.000005)
$Pressure_{i.t-6}$	-0.000000	-0.000011	-0.000004	0.000000	-0.000001	-0.000001
	(0.000001)	(0.000009)	(0.000010)	(0.000001)	(0.000006)	(0.000005)
$Pressure_{i.t-7}$	-0.000001	-0.000011	-0.000003	0.000000	0.000002	-0.000000
	(0.000001)	(0.000009)	(0.000009)	(0.000001)	(0.000006)	(0.000004)
$Pressure_{i.t-8}$	-0.000000	0.000001	0.000022**	0.000000	0.000001	0.000011**
	(0.000001)	(0.000008)	(0.000009)	(0.000001)	(0.000006)	(0.000004)
$Pressure_{i.t-9}$	-0.000001	0.000012	-0.000012	0.000000	0.000009*	0.000004
	(0.000001)	(0.000009)	(0.000009)	(0.000001)	(0.000005)	(0.000004)
$Pressure_{i.t-10}$	-0.000001	0.000006	0.000008	0.000001*	0.000005	0.000004
	(0.000001)	(0.000010)	(0.000009)	(0.000001)	(0.000006)	(0.000004)
$Pressure_{i.t-11}$	-0.000003***	-0.000006	-0.000001	-0.000001**	0.000002	-0.000002
	(0.000001)	(0.000008)	(0.000010)	(0.000001)	(0.000005)	(0.000004)
$Pressure_{i.t-12}$	0.000005***	0.000013	0.000023***	0.000005***	0.000011*	0.000018***
	(0.000001)	(0.000009)	(0.000009)	(0.000001)	(0.000006)	(0.000004)
$Cattle_{it}$	0.000040***	0.000059***	0.000639***	0.000038***	0.000029*	0.000417***
	(0.000003)	(0.000017)	(0.000066)	(0.000002)	(0.000016)	(0.000031)
$bTB\_Dummy_{i,t-1}$	-0.013824***			0.023026***		
	(0.001923)			(0.001292)		
$Test\_Dummy_{it}$	0.065178***			0.070491***		
	(0.000589)			(0.000515)		
$bTB\_Ratio_{i,t-1}$		0.006724			0.035663***	

		(0.010311)			(0.007191)	
$Test\_Ratio_{it}$		0.002872***			0.002114***	
		(0.000543)			(0.000355)	
$bTB\_Number_{i,t-1}$			-0.005652			0.028262*
			(0.007976)			(0.014767)
$Test\_Number_{it}$			0.001191***			0.001262***
			(0.000069)			(0.000049)
Constant	-0.005308***	0.002544	-0.058158***	-0.008855***	-0.014059***	-0.042193***
	(0.000938)	(0.007754)	(0.012223)	(0.000352)	(0.003431)	(0.003482)
Linear combinations of estimated coefficients for urbanization measurements	-0.000336	-0.004056**	-0.001166	0.000032	0.000451*	0.000259
	(0.000246)	(0.001830)	(0.001766)	(0.000023)	(0.000238)	(0.000188)
Herd fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year-month fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3608843	3608843	3608843	10821960	10821960	10821960

Cluster standard errors in parentheses. Standard errors are clustered at the herd level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Appendix D Method for estimating death loss

Our baseline empirical results provide evidence for the externality generated from urbanization on the bTB situation, and we are interested in the monetary loss caused by this externality. In this section, we illustrate the method for how we calculating the death loss result from the urbanization.

To do so, we first construct a regression to estimate the impacts of urbanization on cattle been slaughtered. The reason we redo estimations with cattle been slaughtered as the dependent variable instead of bTB positive reactors is that they are sometimes not equal to each other. According to the UK government, not only are the cattle confirmed to have bTB (bTB positive reactors) slaughtered, but those suspected of having bTB are also slaughtered. Thus, the number of cattle been slaughtered would sometimes exceed the number of reactors. And since we are estimating the death loss, using cattle been slaughtered would be more appropriate and accurate. Further, since we want to synthetically analyze the impacts of urbanization on death loss, we include both the localized and regional urbanization measurements into one regression. Specifically, we use the nightlight measurements as the proxy for urbanization, we estimate the coefficients of Equation D1, and the regression results are provided in Table D1.

$$\begin{aligned} Slaughter_{it} = {} & \alpha + \beta_1 Urbanization_{it} + \beta_2 Urbanization_{rt} + \gamma Slaughter_{i,t-1} + \delta Pressure_{i,t-1} \\ & + \eta Cattle_{it} + \varphi Test_{it} + \lambda h_i + \mu m_t + \varepsilon_{it} \qquad \text{(D1)} \end{aligned}$$

Secondly, with the coefficients estimated by Equation D1, we construct a counterfactual scenario where the localized and regional urbanization level of all the herds are zero. And we calculate the counterfactual changes of cattle been slaughtered because of these changes of urbanization levels. The method for calculating the counterfactual changes is shown below:

$$\begin{aligned} \Delta Slaughter\_Number_{it} & = Slaughter\_Number_{it}^{c} - Slaughter\_Number_{it}^{o} \\ & = -\beta_1 Urbanization_{it}^{o} - \beta_2 Urbanization_{rt}^{o} + \gamma \times \Delta Slaughter\_Number_{i,t-1} \\ & \quad + \delta \times \Delta Pressure_{i,t-1} \qquad \text{(D2)} \end{aligned}$$

Where $\Delta Slaughter\_Number_{it}$ is the counterfactual changes of cattle been slaughtered from the herd i at time t. $Slaughter\_Number_{it}^{c}$ is the counterfactual cattle been slaughtered after setting the urbanization level as zero, where the superscript c means "counterfactual". $Slaughter\_Number_{it}^{o}$ is the original cattle been slaughtered with the real urbanization level, where the superscript o means "original". $Urbanization_{it}^{o}$ is the original localized urbanization level measured by nightlight, $Urbanization_{rt}^{o}$ is the original regional urbanization level. Other symbols are defined similarly as before.

Notice that Equation D2 has lagged variables $\Delta Slaughter\_Number_{i,t-1}$ and $\Delta Pressure_{i,t-1}$. It's natural to think that our counterfactual scenario will also lead to changes in these lagged variables. However, if we allow a change to dynamically affect infinite following periods, it would highly increase the complexity and be more likely to overestimate the impacts of urbanization. Thus, for simplicity and realizability, we use the following Equation D3 to calculate the $\Delta Pressure_{i,t-1}$, and we use the Equation D4 to calculate the $\Delta Slaughter\_Number_{i,t-1}$.

$$\begin{aligned}\Delta Pressure_{i,t-1} &= \frac{\overline{\Delta Slaughter\_Number_{\imath t}}}{\overline{Slaughter\_Number^{o}_{\imath t}}} Pressure^{o}_{i,t-1} = \\ &\approx \frac{-\beta_1 \overline{Urbanization_{\imath t}} - \beta_2 \overline{Urbanization_{rt}}}{\overline{Slaughter\_Number^{o}_{\imath t}}} Pressure^{o}_{i,t-1} \\ &\approx \frac{0.000010 \times 1.18672 - 0.001044 \times 1.18672}{0.03892} Pressure^{o}_{i,t-1} \\ &= \frac{0.0000118672 - 0.00123893568}{0.03892} Pressure^{o}_{i,t-1} \\ &\approx -0.03153 \times Pressure^{o}_{i,t-1} \qquad \text{(D3)}\end{aligned}$$

Where $\overline{\Delta Slaughter\_Number_{\imath}}$ is the average counterfactual changes of cattle been slaughtered in all herds in all periods. $\overline{Urbanization_{\imath t}}$ is the mean of localized urbanization levels, and $\overline{Urbanization_{rt}}$ is the mean of the regional urbanization levels

$$\Delta Slaughter\_Number_{i,t-1} = -\beta_1 Urbanization^{o}_{i,t-1} - \beta_2 Urbanization^{o}_{r,t-1} \qquad \text{(D4)}$$

Finally, with the equations and estimated coefficients above, we are able to build the function for calculating the $\Delta Slaughter\_Number_{it}$, which is shown below:

$$\begin{aligned}\Delta Slaughter\_Number_{it} &= \\ &= -\beta_1 Urbanization^{o}_{it} - \beta_2 Urbanization^{o}_{rt} + \gamma \times \Delta Slaughter\_Number_{i,t-1} \\ &+ \delta \times \Delta Pressure_{i,t-1} \\ &\approx 0.000010 \times Urbanization^{o}_{it} - 0.001044 \times Urbanization^{o}_{rt} \\ &+ \gamma \times \left(0.000010 \times Urbanization^{o}_{i,t-1} - 0.001044 \times Urbanization^{o}_{r,t-1}\right) \\ &+ \delta \times 0.0315 \times Pressure^{o}_{i,t-1} \\ &\approx 0.00001 \times Urbanization^{o}_{it} - 0.00104 \times Urbanization^{o}_{rt} \\ &+ 0.02013 \times (0.00001 \times Urbanization^{o}_{it} - 0.00104 \times Urbanization^{o}_{rt}) \\ &- 0.00005 \times 0.03153 \times Pressure^{o}_{i,t-1}\end{aligned}$$

Thus, we calculated the counterfactual changes of cattle been slaughtered, and we further calculated the counterfactual slaughtered cattle and compared them with the real ones.

Table D1: Regression results of urbanization on cattle been slaughtered

	$Slaughter_{it}$
$Urbanization\_Nightlight_{it}$	-0.00001022
	(0.00011686)
$Urbanization\_Nightlight_{rt}$	0.00104439*
	(0.00058397)
$Pressure_{i.t-1}$	0.00004873***
	(0.00000807)
$Cattle_{it}$	0.00055844***
	(0.00005239)
$Slaughter_{i,t-1}$	0.02013411*
	(0.01066237)
$Test\_Number_{it}$	0.00124741***
	(0.00006576)
Constant	-0.04331127***
	(0.00621394)
Herd Fixed Effects	Yes
Year-Month Fixed Effects	Yes
Observations	5024081

Cluster standard errors in parentheses. Standard errors are clustered at the herd level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Appendix E Supplementary tables and figures

Figure E1: Map of 2016 Local Authority Districts (LADs)

Data source: Office for National Statistics of UK government