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Computing metrics to inform selection of candidate areas for a regionalized approach to bovine tuberculosis eradication in Ireland.

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Abstract

We describe the computation of metrics to inform the selection of areas for a regionalised approach to bovine tuberculosis eradication in Ireland. Our aim was not to recommend suitable regions but to elucidate the criteria used in metric selection and comment on the diversity of metric values amongst regions. The 26 counties of Ireland were compared using 20 metrics, grouped into five categories: region size and cattle population, herd fragmentation, cattle movement, bovine TB testing, badger population and control. Fragmentation metrics, measuring the proportion of herds with land in at least two counties, varied considerably by county, from 1% to 24 %. Between 25 % and 92 % of moves into herds came from a different county, illustrating the likely disruption in trade that a regionalized approach could entail. Cattle movement networks were combined with a risk model to calculate the proportion of moves which would be deemed risky under a risk-based trading regime and these results were compared to a more traditional approach based on the herd type and test history of each herd, with many fewer moves potentially restricted using the latter approach. We show how correlation between region size and some of the metrics complicates their interpretation.

Keywords

Regionalization, Metrics, Bovine tubercolosis, Disease eradication, Ireland

Introduction

Regionalization is a well-recognised approach to the control and eradication of animal diseases. It refers to the establishment and maintenance of distinct subpopulations of animals with specific health status within a territory, either through geographic separation (termed *zoning* by the World Organisation for Animal Health) or management and husbandry practices related to biosecurity (termed *compartmentalisation*) (World Organisation for Animal Health, 2023). Typically, this approach leads to the establishment of geographical boundaries around subpopulations of farms with similar disease status to which targeted control measures are imposed, such as movement restrictions, testing and/or vaccination, to minimize the risk of infection/disease spreading from higher to lower risk regions (Hidano et al., 2016; World Organisation for Animal Health, 2023). Collectively this approach enables forward momentum towards improved national infectious disease control.

Regionalization has been a central strategy in many national control and eradication programmes for bovine tuberculosis (bTB), including Australia (More et al., 2015), Mexico (Livingstone et al., 2006), New Zealand (Livingstone et al., 2006), Spain (Bezos et al., 2023), UK (Fielding et al., 2020) and USA (Grear et al., 2014). As with other animal health issues, regionalization is being used to create risk boundaries, thereby allowing disease control and surveillance to be differentiated on the basis of risk, to prioritise resource allocation, and to protect lower risk areas. In Australia, regionalization was used throughout the 27-year national bTB eradication programme, with regional boundaries shifting as progress was made (More et al., 2015). In contrast to the international experience, the Irish bTB eradication programme does not differ by region. Rather, controls vary at a more granular level on the basis of the infection history of herds and outbreak localities.

bTB is endemic amongst Ireland's cattle population, and transmission mechanisms may include contact between cattle, within the same herd and from other herds (both across farm boundaries and from trade between herds), contact with infected wildlife, especially badgers (*Meles meles*), and exposure to the causative organism, *Mycobacterium bovis*, in the wider environment (More and Good, 2015, Broughan et al., 2015). A national eradication programme has been in operation since 1954, and now includes annual testing of all herds, restriction of cattle sales from all herds which test positive, and culling of badgers in areas where they are thought to contribute to bTB outbreaks (Sheridan et al., 2014, Allen et al., 2018, Ryan et al., 2023). After a sharp decline in bTB prevalence in the years following the start of the programme, and a less dramatic, but steady, decline in the decades thereafter, total eradication of bTB in Ireland has proved elusive (More, 2019).

The Irish TB 2030 Stakeholder Forum was established in 2018 and tasked with drawing up proposals to assist with bTB eradication from the national herd by 2030. In recent years, however, progress towards this goal has stalled, following a worsening in national bTB infection metrics, including herd- and animal-level prevalence (More, 2019, 2023). Given this context, the TB Forum has considered a number of policy options, including the potential of regionalization in bTB eradication. With this approach, it is recognised that a suite of enhanced control measures could be implemented in certain areas of the country, with the aim of preventing the inward movement of *M. bovis* into a region and effectively addressing all infection sources within the region.

There is also awareness of the factors which might make a regionalised approach more complex and difficult to achieve, such as the relatively even spatial distribution of bTB and the existing cattle trading patterns within the Republic of Ireland (subsequently termed Ireland), where long distance movements occur frequently (Tratalos et al, 2020) and the fact that many herds use land parcels far away from the home farm (Bradfield et al., 2021, McGrath et al. *in press*). Badger culling has been used as a bTB control mechanism since the 1990s (Griffin et al., 2005) but is now being replaced by badger vaccination across approximately half of the country (Ryan et al. 2023). A regionalised approach would need to be cognisant of the need to control bTB in badgers.

This paper describes the computation of metrics to inform selection of candidate areas for a regionalised approach to bTB eradication in Ireland. This work was undertaken in support of a broader project, conducted by the scientific working group (SWG) of the TB Forum, to consider the potential effectiveness of a regional approach to facilitate bTB eradication in Ireland (Griffin et al., 2024), and the set of metrics we describe was devised in consultation with the stakeholders in this project.

Methods

General Approach

As a first step in this process, we chose counties as our candidate areas; counties are the main administrative divisions in Ireland (N= 26, Figure 1). This allowed the calculation of a range of metrics for each county and in turn allowed us to examine how each metric varied spatially across Ireland. The insights gained from this step would in the future guide the potential creation of additional candidate regions for enhanced control measures.

These metrics fell under five broad categories. 1. *Region size and cattle population metrics*, to provide information on the size and density of the cattle population and the area of each county. 2. *Herd fragmentation metrics*, to examine the degree to which individual herds might be located in more than one county, as this would provide challenges for regional management. 3. *Cattle movement metrics*, to estimate how cattle trade might be affected by risk-based trading, a possible enhanced control mechanism which could be used in selected regions, and to estimate the degree to which movement occurs from one county to another. 4. *Bovine bTB metrics*, to examine bTB prevalence and resources available to manage bTB control. 5. *Badger data*, to provide information on badger abundance in the county and the degree to which badger control operations and badger vaccination are conducted there.

With the exception of badger data metrics, 2019 was chosen as the year over which to calculate these metrics, as four of the cattle movement metrics (metrics 8,9,12 and 13, described in the Methods section) were calculated using a statistical model calibrated for 2018 and 2019 (Tratalos et al., 2023).

Mapped output was produced using ArcGIS Pro 3,2,0, data queries were run in Microsoft SQL Server, and Pearson correlations, tables and figures were produced in Microsoft Excel.

The Metrics

Region size and cattle population metrics.

Information on the size of each county and its cattle population was provided with the following three metrics. Metric 1: Land area (in square kilometers). Metric 2: Density of herds. Ireland's Animal Identification and Movement (AIM) dataset (McGrath et al., 2018) was used to generate a list of all herds containing animals on 1st January 1st May or 1st September in 2019. For most herds, herd locations were determined as the centroid of the largest land fragment occupied by the farm, a proxy for the home farm, based on the 2018 version of the Land Parcel Information System (LPIS) produced by the Department of Food, Agriculture and the Marine (DAFM) (Zimmermann et al., 2016). Where this information was not available, the geographic coordinates for the herd's location were assigned by generating a random point within the District Electoral Division to which the herd is assigned. Electoral divisions (EDs) are the smallest legally defined administrative area for which Small Area Population Statistics (SAPS) are published from the Irish Census (N = 3,440). The number of herds in each county was then divided by its land area, to obtain the number of herds per square km. Metric 3: *Density of cattle*. The number of cattle in each county was calculated in the same way as the number of herds, based on the AIM dataset, but in this case, the cattle population of each herd was used. For each herd, the bovine population was estimated as an average of the number of animals present in the herd on 1st January 1st May and 1st September 2019. The number of cattle was divided by the land area of each county (Metric 1), to obtain the number of cattle per square km.

Herd fragmentation metrics

We wanted to know the degree to which the land used by a herd was restricted to a single county because targeted controls in a given area were likely to be more effective in cases where cattle were not able to move outside the county whilst staying within the same herd. We therefore calculated two metrics measuring herd fragmentation between counties; both of these metrics were computed using the 2019 LPIS data: Metric 4: Percentage of herds with their home farm in the county and at least one land parcel outside it. Metric 5: Percentage of herds with their home farm outside the county and at least one land parcel within the county. Land parcels less than one kilometre outside the county were not classified as 'outside'.

Cattle movement metrics

Cattle movement metrics were generated from the AIM dataset, which lists all bovine births and movements between cattle herds on an individual animal basis, and is described in detail in Tratalos et al. (2020, 2023) and McGrath et al. (2018). Herd keepers have a legal obligation to notify DAFM of the movement of cattle to and from their holdings (Department of Agriculture, Food and the Marine, 2023, Tratalos et al., 2020). These data were used to estimate movement network variables and herd size. In the foregoing, when we use *moves*, we mean individual animals – e.g., if a herd sells three of its animals to another herd that counts as three moves. We calculated the percentage of moves which originated in herds located outside of the county, as well as a series of metrics to measure "risky" moves, which might be restricted under enhanced control measures.

We measured risky moves in two ways. The first method was in accordance with criteria devised by Ireland's Department of Agriculture, Food and The Marine (DAFM), which we will call the *DAFM method*. Under this method, a risky move involves the sale of cattle from a breeding herd which has had at least one breakdown (i.e. herd restriction resulting from the identification of bTB animals) in the last three years involving at least five animals, and did not have controlled finishing unit (feedlot) status at the time of the move, to a herd which does not fulfil these criteria.

The alternative method to estimate risk used a statistical model, published as the 'history and proximity model' in Tratalos et al. (2023). This model determined that the risk of a breakdown in an Irish herd during the years 2018 or 2019 could be estimated using a number of variables related to the bTB testing history of the herd, of herds nearby to it and of herds trading into it, as well as herd type and size, the movement network measure 'betweenness', altitude, and a model of badger abundance derived by Byrne (2014). Full details of the model are given in Tratalos et al. (2023).

Whilst using these two ways to measure risk we calculated separate metrics for the county of the buying herd and of the selling herd, although it should be noted that for many cattle moves both buying and selling herd would be in the same county. For these four combinations (2 risk x 2 herd location measures) we calculated separate metrics for the percentage of herds affected and the percentage of moves affected, based on 2019 data, resulting in the creation of 8 metrics. These metrics were therefore as follows. Metric 6: Percentage of **moves** from herds considered high risk according to **DAFM criteria** to herds considered lower risk, with reference to the county of the **selling** herd. Metric 7: Percentage of **moves** from herds considered high risk according to **DAFM criteria** to herds considered lower risk, with reference to the county of the **buying** herd. Metric 8: Percentage of **moves** from herds considered high risk based on the **model** of Tratalos (2023) to herds considered lower risk, with reference to the county of the **selling** herd. Metric 9: Percentage of **moves** from herds considered high risk based on the **model** of Tratalos (2023) to herds considered lower risk, with reference to the county of the **buying** herd. Metric 10: Percentage of **herds** which **sold** animals from herds considered higher risk according to **DAFM criteria**. Metric 11: Percentage of **herds** which **bought** animals from herds considered higher risk according to **DAFM criteria**. Metric 12: Percentage of **herds** which **sold** animals from herds considered higher risk based on the **model** of Tratalos (2023). Metric 13: Percentage of **herds** which **bought** animals from herds considered higher risk based on the **model** of Tratalos (2023). One further metric was calculated, Metric 14, which measured the percentage of inward moves to herds in the county where the selling herd was in a different county.

Bovine TB incidence and testing metrics

Metrics measuring bTB incidence and testing were derived from DAFM's Animal Health Computer System (AHCS). This dataset gives the bTB test history of each herd in Ireland, comprising results of the Comparative Intradermal Tuberculin Test (CITT, formally known as the Single Intradermal Comparative Tuberculin Test, SICTT), interferon-gamma (IFN-γ) tests and slaughterhouse inspections. The identity of attending veterinarians is also given for each herd test. Each Irish cattle herd is tested at least once per year. Three metrics were produced from DAFM bTB test and surveillance data for CITT, IFN-γ, and lesions for each animal tested in 2019.

Metric 15: bTB herd incidence. The bTB herd incidence was calculated in accordance with the definitions laid down in footnotes d, e and f of Annex III Table A of Commission Implementing Decision of 2014/288/EU. Metric 16: Animal bTB incidence. Cases consisted of all reactors (for CITT and IFN-γ tests) and laboratory confirmed *M. bovis* infections in slaughtered cattle (culture positive). The denominator used to calculate incidence was the cattle population in the county on 31/12/2019. Metric 17: Private Veterinary Practitioners (PVPs) per 1,000 cattle herds. As a proxy for this, we used the number of attending veterinary practitioners per 1,000 herds at CITT tests carried out in the county.

Badger population and control metrics

We calculated metrics on badger control and vaccination for each county using data from the DAFM wildlife unit datasets (Byrne et al., 2015). These data record the sett locations and number of badgers caught and euthanised, as well as vaccinated, under the bTB eradication programme. We also had access to information on which areas had been designated for badger vaccination, as of February 28th, 2022. We used the mapped output from Byrne et al. (2014), which estimates the probability of the occurrence of a badger social group (strictly a main sett), at 100 m resolution, as a proxy for badger abundance. This resulted in a further three metrics. Metric 18: Percentage of the area in the county included within the badger vaccination programme. Metric 19: Total badgers culled or vaccinated, 2018 to 2022. Metric 20: Average pixel value (1 ha square area) from Byrne (2014) badger abundance model.

Relationships between area size (Metric 1) and other metrics

Ideally, each metric could be derived in such a way that areas of different sizes could be compared to each other without these size differences affecting how each area ranked relative to the others. However, for some of our metrics (detailed below), this is unlikely to be true. To explore this, Pearson correlations were calculated between Metric 1 (land area) and the following five metrics: Metrics 4 and 5 (the herd fragmentation metrics), Metric 14 (percentage of moves coming from outside the county), Metric 17 (the number of attending vets per 1,000 herds) and Metric 18 (the proportion of the county covered in the badger vaccination programme).

Results

Metrics 1-3: Region size and cattle population

Figure 1 Shows the location of each county and illustrates how they vary in size. Note that counties in the West of Ireland are generally larger than those in the East. This is worth bearing in mind for other metrics which measure density, as larger counties will, *ceteris paribus*, contain a larger number of herds, badgers etc.

Each of metrics 2-20 is mapped for each county using a blue choropleth legend in Figure 2. Table I gives the numeric values for each metric, with each cell coloured using a similar choropleth to that used in the maps. For each map, and across the metrics shown in Table I, the choropleth is divided into 12 quantiles, or *dodeciles*, with the darkest blue representing the highest values and the lightest blue the lowest.

Counties in the north and west typically had the highest densities of herds and those in the south and midlands typically had relatively high densities of cattle (Table I, Figure 2)

County	Herds	1.Area (sq. km)	2. Herd Den	3. Cattle Den	4. Frag Out	5. Frag In	6. RM_D_s	7. RM_D_b	8. RM_M_s	9. RM_M_b	10.RH_D_s	11.RH_D_b	12.RH_M_s	13.RH_M_b	14.Moves In	15.Hd Incid x 10^4	16.An Incid x 10^4	17.Vets/1000 hds	18. % Vax.	19. Badg / Km	20. Badg. Mod
Carlow	1,393	897	1.55	127	11.1	9.6	1.9	4.0	30	30	1.1	9.9	26	40	80	29	1.0	28	79	0.69	0.41
Cavan	4,623	1,912	2.42	116	6.6	6.4	6.8	5.9	36	47	3.5	13.8	45	46	58	46	4.6	13	20	0.90	0.41
Clare	5,948	3,184	1.87	87	2.2	2.1	7.0	7.1	38	46	4.0	12.7	46	46	25	47	4.9	9	3	0.72	0.38
Cork	11,388	7,438	1.53	142	2.1	2.2	6.7	6.2	48	45	3.4	10.4	44	42	28	46	3.2	13	23	0.54	0.40
Donegal	5,080	4,851	1.05	37	0.8	0.8	1.0	1.9	34	31	0.7	4.3	36	38	26	23	1.6	6	13	0.24	0.20
Dublin	321	915	0.35	21	24.1	12.5	7.8	4.3	32	14	4.4	13.1	27	30	92	53	7.4	90	1	0.13	0.24
Galway	10,726	6,084	1.76	70	3.6	2.8	3.1	3.5	34	47	1.6	8.1	37	43	41	28	3.2	9	19	0.32	0.30
Kerry	6,331	4,743	1.33	69	2.6	2.6	5.4	5.8	41	53	2.7	8.4	41	46	40	28	2.9	12	19	0.42	0.29
Kildare	1,962	1,695	1.16	93	13.1	11.5	2.2	5.1	34	23	1.1	14.0	20	36	79	32	1.1	33	35	0.87	0.39
Kilkenny	2,885	2,063	1.40	166	6.2	5.9	4.9	4.7	43	38	2.0	10.8	41	48	61	43	1.7	25	75	0.85	0.44
Laois	2,589	1,717	1.51	139	8.1	7.3	4.2	4.9	37	35	2.0	14.7	37	51	66	43	2.1	25	51	0.88	0.37
Leitrim	2,582	1,528	1.69	39	12.0	10.7	1.5	3.8	26	50	1.6	5.6	41	36	75	26	4.1	18	66	0.80	0.31
Limerick	5,262	2,683	1.96	154	6.1	5.5	3.8	4.7	43	49	1.7	13.2	37	49	52	21	1.1	22	38	0.47	0.43
Longford	2,338	1,042	2.24	108	9.9	8.6	1.7	5.1	30	38	0.9	10.3	37	48	73	22	1.5	23	95	0.65	0.40
Louth	1,193	823	1.45	118	8.9	6.8	5.5	4.8	41	28	2.2	15.3	28	41	81	55	3.0	19	71	0.86	0.37
Mayo	8,809	5,566	1.58	48	2.8	3.0	2.4	3.1	33	44	1.1	6.5	39	43	41	16	1.8	8	27	0.31	0.23
Meath	3,212	2,339	1.37	119	10.3	9.8	7.2	5.1	41	21	3.1	19.7	37	45	71	56	2.6	29	43	0.37	0.43
Monaghan	4,150	1,295	3.20	162	3.0	2.8	9.7	7.9	37	41	4.4	19.2	35	46	53	70	7.4	8	31	1.27	0.46
Offaly	2,790	1,997	1.40	112	9.5	8.0	4.5	4.3	36	38	2.4	17.1	34	50	67	51	3.0	26	40	0.71	0.38
Roscommon	5,213	2,479	2.10	80	7.6	7.3	2.3	3.1	33	34	1.3	10.1	42	48	66	31	3.0	12	26	0.60	0.37
Sligo	3,378	1,791	1.89	60	6.3	6.2	3.5	3.6	34	43	1.8	8.7	43	41	60	29	2.5	17	13	0.53	0.30
Tipperary	6,720	4,250	1.58	163	5.4	5.9	5.1	5.1	41	40	2.9	14.1	37	47	46	35	2.3	19	46	0.81	0.40
Waterford	2,068	1,839	1.12	138	5.4	4.6	3.3	3.7	43	45	1.7	9.6	41	50	39	24	0.8	25	36	0.63	0.41
Westmeath	3,139	1,800	1.74	125	10.4	10.2	6.9	5.7	39	32	3.2	16.1	37	44	76	52	3.7	29	6	0.87	0.43
Wexford	2,740	2,354	1.16	119	2.9	2.9	5.9	4.5	41	37	3.1	13.2	43	46	40	49	2.8	17	32	0.68	0.41
Wicklow	1,324	2,025	0.65	53	9.6	10.1	8.3	8.0	36	31	7.6	13.6	48	40	78	105	11.9	30	9	0.63	0.31

Table I. Values for all of the metrics calculated for each county based on 2019, with cells formatted by a choropleth in which the data are divided into 12 equal frequencies, or dodeciles, separately for each metric. Titles for each metric consist of the number given to it in the methods section of the text and an abbreviated form of its name. Note that for Metrics 6-17, which all measure animal movements which might be disallowed under risk-based trading, R stands for Risk-based trading metric; m stands for % of moves, as opposed to h, % of herds; D stands for risk based on DAFM criteria, as opposed to M, risk based on model (Tratalos, 2023); and s stands for based on county of seller, as opposed to b, based on county of buyer. See the methods section of the text for a detailed description of the metrics. Also given is the total number of herds in the county, based on 2019 data, which is the denominator for some of the metrics.

Figure 1. The counties of Ireland, showing the differences in land area (Metric 1) between each.

Metrics 4 and 5: Herd Fragmentation Metrics

The percentages of herds which had land patches outside their home counties were similar to those for the percentages of herds with patches in the county which had their home patch in another county and was generally larger for smaller counties. These proportions varied from about 1 % (Donegal, both metrics) to 24 % (Dublin, latter metric) (Table I, Figure 2).

Metrics 6 to 14: Cattle Movement Metrics

Metrics 6 to 13, which measure the percentage of moves from higher to lower risk herds, generally gave low values in the northwest counties, from Mayo to Donegal, and higher in the south and east, although this pattern was not evident for metrics 9 and 12 (Table I, Figure 2). Metrics 6,7, 10 and 11, which measured risk according to the DAFM definition of a risky herd, showed much lower values (range: 1.53 – 19.71) than metrics 8,9,12 and 13, which were based on whether the selling herd had a higher probability of a breakdown according to the model of Tratalos et al. (2023) (range: 13.54-52.67). This would be expected given the much higher number of herds included in the latter definition. As might be expected, smaller counties had a larger proportion of moves coming from outside the county, with Dublin (92 %) the highest and Donegal (26 %) the lowest (Table I, Figure 2).

Metrics 15-17: bTB

bTB herd incidence in 2019 was generally highest towards the east of Ireland, with counties Cork and Clare also showing somewhat high values, but this pattern was not evident for animal bTB incidence, which varied from 7.58 per 10,000 animals (Waterford) to 119.05 per 10,000 animals (Wicklow) (Table I, Figure 2). The number of attending PVPs per 1,000 herds was highest in the east of Ireland, and especially in county Dublin, which was almost 3 times higher than the next highest county, Kildare (90.3 versus 33.1). (Table I, Figure 2).

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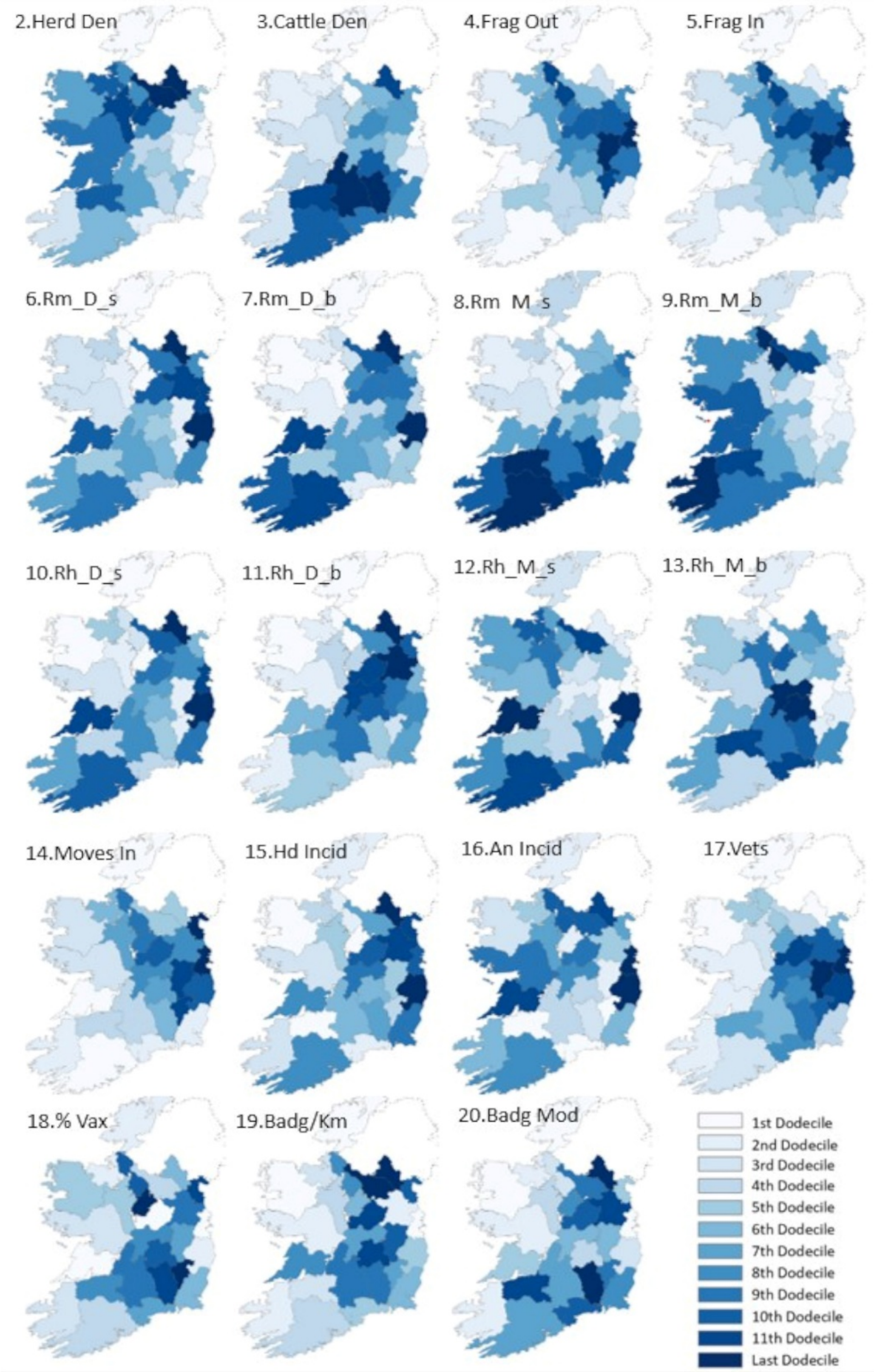

Figure 2. Metrics 2-20, in each case illustrated by a choropleth in which the data are divided into 12 equal frequencies, or dodeciles (see legend, bottom right). Titles for each metric consist of the number given to it in the methods section of the text and an an abbreviated form of its name. Note that for Metrics 6-17, which all measure animal movements which might be disallowed under risk-based trading, R stands for Risk-based trading metric; m stands for % of moves, as opposed to h, % of herds; D stands for risk based on DAFM criteria, as opposed to M, risk based on model (Tratalos, 2023); and s stands for based on county of seller, as opposed to b, based on county of buyer. See the methods section of the text for a detailed description of the metrics.

Metrics 18-20: Badger data

The percentage of each county enlisted within the badger vaccination programme ranged from less than 10% in Dublin, Clare, Westmeath and Wicklow to over 70% in Louth, Kilkenny, Carlow and Longford (Table I, Figure 2). The density of badgers culled or vaccinated varied considerably across Ireland, from 0.13 badgers per Km in County Dublin to 1.27 in Monaghan (Figure 2). Values for this metric were often high in central counties such as Cavan (0.9), Laois (0.88) and Westmeath (0.87). Conversely, suitability for a badger social group (as modelled by Byrne et al., 2014) did not vary greatly, with a lowest value of 0.2 (County Donegal) and high of 0.46 (Monaghan) (Table I, Figure 2).

Relationships between area size (Metric 1) and other metrics

There were strong negative correlations between Metric 1 (area) and metrics 4 and 5 (the herd fragmentation metrics), r = -0.62, -0.66, and Metric 14 (the percentage of moves coming from outside the county), r = -0.75 (Figure 3). Weaker negative correlations were observed between Metric 1 and Metrics 17 (number of attending veterinarians per 1,000 herds), r = -0.45 and 18 (% of the county covered by the badger vaccination programme), r = -0.37 (Figure 3).

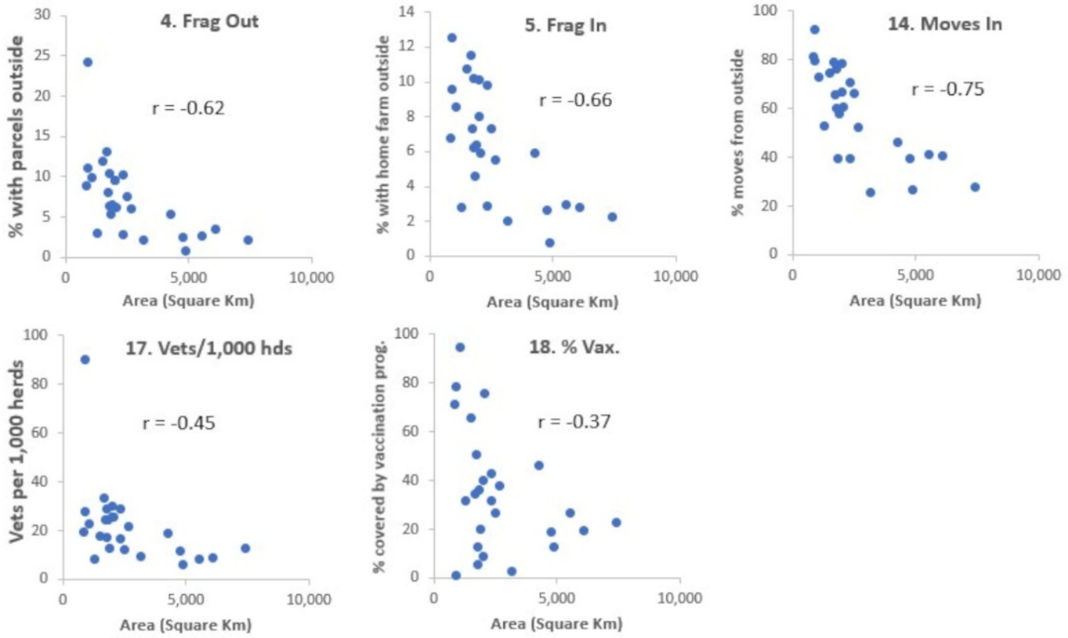

Figure 3. Relationships between the area of each county (Metric 1) and five other metrics. Titles for each metric consist of the number given to it in the methods section of the text and an abbreviated form of its name. See the methods section of the text for a a detailed description of the metrics.

Discussion

The aim of this study was to derive a variety of metrics which might be used to inform selection of candidate areas for a regionalised approach to bTB control. These metrics were chosen after considering both the overall purpose of regionalization (the establishment, through geographic separation, and maintenance of distinct subpopulations of animals with specific health status within a territory) and key objectives to be achieved to ensure that regionalization is successful (preventing the inward movement of *M. bovis* into a region and effectively addressing all infection sources within the region).

In the case of bTB, these metrics would need to consider both cattle and wildlife, as well as the degree to which control and surveillance within the region, may be able to meet logistical challenges, such as enhanced cattle testing and wildlife measures (Griffin et al., 2024). Part of the challenge in devising such metrics is to bring the gap between policymakers, who may have a clear understanding of what information they would need for each region, and data scientists, who may have a better understanding of the available data and its limitations. We believe that working in consultation with a range of stakeholders with a strong experience of the Irish bTB programme, we have devised a set of metrics which address their information needs using currently available data.

In the current study, a number of metrics focus on factors that could be used to identify or differentiate regions that could be considered for an area-based approach to bTB control. These metrics relate to region size and cattle population (Metrics 1-3), land fragmentation (Metrics 4 and 5), cattle movement (Metrics 6-15), bovine bTB (Metrics

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15-17) and badger populations (Metrics 18-20).

The region size metric (Metric 1) is important as firstly, the size of a region has implications for the logistics of a control programme, with larger regions requiring more resources to implement farm visits and wildlife control. Secondly, this measure gives context to some of the other metrics, both because in some cases they have already been normalized by area and also because some metrics, for example Metrics 4 and 5 (the herd fragmentation metrics) and Metric 14 (percentage of cattle moves coming from outside the county), would be expected to show a positive or negative relationship with region size irrespective of differences at the farm level, and Figure 3 shows this to be true. It would be important to bear this in mind when comparing the suitability of different regions for a regionalised approach when these regions are of different sizes, and, in such cases, alternative versions of these metrics could measure the degree to which a given region shows a higher or lower value than would be expected given its size. It is interesting that the number of veterinarians attending CITT tests per 1,000 herds (Metric 17) also showed a negative relationship with region size, and this may be because vets tend to be more concentrated around areas of higher human populations which in Ireland tend to be concentrated in the smaller counties. A negative relationship between region size and the badger vaccination metric (Metric 18) may be due to a tendency for badger vaccination currently to be concentrated in those counties with good quality farmland, which in many cases are smaller than average. Further research could examine the reasons for the relationship between region size and these two metrics.

The herd and cattle population metrics (Metrics 2 and 3) similarly indicate the degree of logistical challenge implied in disease control and can be multiplied by Metric 1 to derive the absolute numbers of herds and cattle in a region. In Ireland, areas of high cattle density do not necessarily correspond with areas of high herd density, as herd sizes tend to be much larger in areas of the country dominated by dairy farms, where there are fewer but larger, herds (Tratalos et al., 2020).

In Ireland, farms are often fragmented, at times substantially so, with one or more fragments somewhat distant from the home farm location (Bradfield et al., 2021, McGrath et al., *in press*). Fragmentation poses particular problems for a regional approach, as it in some cases allows herd owners to move animals from one region to another without restriction, as they are not required to register within-farm movements, including those between distant fragments. Metrics 4 and 5 therefore reflect the degree to which this might prove to be an issue for each county in a regionalized approach, revealing the variability in how fragmentation would enable this uncontrolled movement of cattle between regions.

The movement of *M. bovis* from one region to another can occur through the movement of infected cattle between farms, of infected cattle between fragments of the same farm, and of infected wildlife (Tratalos et al., 2023, Ryan et al. 2024, Byrne Milne et al., 2022). Metrics 6-13 address the inward movement of cattle between farms, with a focus on high-risk movements (that is, animals moving along a risk gradient from higher to lower risk). Such movements might be restricted under risk-based trading regimes currently under consideration and, under a regionalised approach, might be restricted to certain regions. The indicators reveal how the burden on herd owners of such an approach might differ from one region to another, and the extent to which a focus on the selling or buying herd, and also the method used to determine a risky move, will affect this. Clearly it would be ideal if any risk based trading or other measures that restricts the movement of animals would have an effect only on those regions where the restriction was applied. However, metric 14 shows that counties have between 25 and 92 per cent of inward moves coming from other counties.

The bTB infection metrics show the variability in infection (Metrics 15 and 16) and give an indication of the number of veterinarians (Metric 17) able to engage with any enhanced control mechanisms, such as pre-movement testing or engagement with herd owners. In counties shown to be in lower duodeciles for Metric 17, but in higher duodeciles for Metrics 15 and 16, it might be particularly challenging.

Although it was not possible to devise direct measures of the potential for inward movement of infected wildlife, Metrics 18-20 provide some insight into the abundance of badgers and levels of bTB control-related culling and vaccination of these populations. Ideally, any region selected for enhanced bTB control would be one in which badger population densities were low, and, in the absence of direct measures of abundance, Metric 20 is perhaps the best proxy for this. Ideally these same regions would be ones where badger control operations operated efficiently; Metrics 18 and 19 measure this to some degree, as they reveal those regions with a history of high levels of badger culling or vaccination. However, caution should be excised here as badger culling (a component of Metric 19) is also likely to track bTB infection and the degree to which badgers have been identified as having a role in it. Perhaps a better indicator of control efficiency would be to normalize the data shown in Metric 19 with some measure of effort, but effort measures were not available to us. With respect to containing wild animal infection, Livingstone et al. (2006) have noted that knowledge of the ecology, habitat, population densities, and natural routes and boundaries to migration for the species of concern are all important when determining where boundaries should be located.

Table I and Figure 2 highlight the substantial diversity of metric values across the 26 Irish counties and demonstrate the challenges involved in selecting a suitable region, as no single county is highly favourable for all metrics. Nonetheless, there are several counties, predominantly in the west, where many of the metrics appear to indicate that enhanced controls might be easier to achieve and less disruptive than elsewhere. For example, Donegal measures well on the farm fragmentation metrics (Metrics 4 and 5), has only one cattle movement metric noticeably above the minimum duodecile (Metric 8), and also has a low herd and animal bTB incidence (Metrics 15 and 16); Mayo is similar to this – 6 out of 9 of the movement metrics, as well as the 2 herd fragmentation and 2 bTB incidence metrics, all fall between the second and fourth duodecile.

The purpose of this study was not to select or otherwise provide recommendations for suitable regions. That would require a further study, including the prioritisation of these (and potentially other) metrics, which would need to be conducted in close collaboration with national policymakers. Rather, in this paper we highlight the criteria used to guide metric selection and present commentary on the diversity of metric values across the counties of Ireland.

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Availability of data and materials

The datasets generated during the current study are available from the first author on reasonable request.

Authors' contributions

JT did most of the data processing, conducted the analysis and wrote the manuscript. JM produced the bTB data sets used in the analyses, provided advice on study design and statistics and contributed to the draft. GM provided the badger and LPIS data used in the analyses, provided advice on study design and contributed to the draft. SM contributed to the initiation of the study, provided advice on study design and contributed to the draft.

Competing Interests

The authors declare that they have no competing interests**.**

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