Running title: BVDFree England data analysis

Descriptive analysis of national bovine viral diarrhoea test data in England

Naomi S. Prosser[1*†], Edward M. Hill[2,3†], Derek Armstrong[4,5], Lorna Gow[4,5], Michael J. Tildesley[2,3], Matt J. Keeling[2,3], Jasmeet Kaler[1], Eamonn Ferguson[6], Martin J. Green[1]

[1]School of Veterinary Medicine and Science, University of Nottingham, Sutton Bonington Campus, Leicestershire, LE12 5RD, UK

[2]The Zeeman Institute for Systems Biology & Infectious Disease Epidemiology Research, School of Life Sciences and Mathematics Institute, University of Warwick, Coventry, CV4 7AL, UK

[3]Joint UNIversities Pandemic and Epidemiological Research, https://maths.org/juniper/

[4]BVDFree England Scheme, Stoneleigh Park, Kenilworth, Warwickshire, CV8 2TL, UK

[5]Agriculture and Horticulture Development Board, Stoneleigh Park, Kenilworth, Warwickshire, CV8 2TL, UK

[6]School of Psychology, University Park, University of Nottingham, Nottingham, NG7 2RD, UK

[*]Corresponding author: naomi.prosser@nottingham.ac.uk

[†]Authors contributed equally

Abstract

Background: Bovine viral diarrhoea virus (BVDV) causes substantial economic losses to cattle herds; however, control and eradication can be achieved by identifying and removing persistently infected cattle. Each UK nation has separate control programmes. The English scheme, BVDFree, started in 2016 and is voluntary.

Methods: We analysed the test results submitted to BVDFree from 5,847 herds from 2016 to 2020.

Results: In 2020, 13.5% of beef breeder herds and 20.0% of dairy herds had at least one positive test result. Though lower than in previous years, there was no clear trend in the proportion of positive tests over time. In antigen testing herds, 1.5% of tests from antigen positive herds were positive, which was 0.4% of tests from all antigen testing herds. Dairy herds and larger herds were more likely to join BVDFree and dairy herds were also more likely to antigen test than beef breeder herds. Larger herds, herds that used individual antigen testing and herds that had BVD positive test results were more likely to continue submitting tests to BVDFree.

Conclusions: The findings provide a benchmark for the status of BVD control in England; continued analysis of test results will be important to assess progress towards eradication.

Key words

Antibody testing, Antigen testing, Bovine viral diarrhoea, BVDFree England, Disease eradication scheme

Introduction

Bovine viral diarrhoea virus (BVDV) is a pestivirus that affects cattle and is endemic in the UK. BVDV infections in a herd causes diverse production losses such as reduced fertility, decreased milk yield, abortions, increased susceptibility to other diseases, poor growth rates and mucosal disease[1,2].

Infection is largely maintained by the presence of persistently infected (PI) animals, which are created when a cow becomes infected prior to immunocompetence in the developing calf (within the first 120-125 days of gestation)[3]. PI animals shed BVDV their entire life, whereas immunocompetent cattle infected with BVDV ex-utero are only transiently infected and develop lifelong immunity. In 2021 the Ruminant Health & Welfare Group suggested a target to eradicate BVDV from the UK by 2031[4].

In order to control and eradicate BVDV, PI animals must be identified and removed from the herd[5]. There are two strategies commonly used for PI identification in herds: antigen or antibody testing[6,7]. Individual antigen (or viral) tests are used to detect BVDV infected animals and are usually conducted as tissue tests, often incorporated into the identification tag. For antibody testing, a sample of unvaccinated cattle from specific management groups (commonly 9-18 months of age) are tested for exposure to BVDV. Individual antigen or virus testing is required following a positive antibody test to identify any animals persistently infected with BVDV. The antigen and virus tests are unable to distinguish between transient and persistent infections, therefore follow up testing is recommended to confirm a PI animal[8].

A number of countries have had success in BVD control and eradication, using both antigen and antibody testing regimes[9]. BVD control in the UK is conducted by schemes in each of the home nations which are diverse in terms of testing used, mandatory participation and progress[10]. A voluntary scheme commenced in Scotland in 2010 before becoming mandatory in 2013[11]. In this scheme, farmers could use either an antibody screen or antigen test for all calves[11]. The prevalence of BVD in Scotland declined between 2010 and 2019 from 40% to 10% of herds[12]. Northern Ireland's scheme, which uses antigen testing (via ear tag) on every calf, was voluntary when introduced in 2013 and became mandatory in 2016. There was a decrease in herd-level prevalence from 11% to 4.17% from 2016 to 2021[13]. Wales has a voluntary scheme (Gwaredu BVD), funded by the Welsh Government's Rural Development Programme, that started in 2017 and offers free youngstock antibody screening, with limited additional funding for identifying PI animals[14]. Changes in BVD prevalence over the first three years (to 2020) have not been published for Gwaredu BVD. Elsewhere in the British Isles, Ireland has reduced its herd-level prevalence of BVD following the introduction of a compulsory programme (tissue tagging of all calves born since 1st January 2013) with an estimated prevalence of BVD in herds of 11.3% at the start of 2013 reducing to 0.55% in 2020[15]. BVD control became compulsory in the Isle of Man in 2014 and no PI cattle have been detected since 2018[16].

BVDFree England (hereafter referred to as BVDFree) is the voluntary BVD eradication programme for England that started in 2016[17]. Members of BVDFree are required to upload the results of all testing for BVD to the BVDFree database. Two years of testing is required in order to achieve a negative status, which can be achieved through either an antigen/virus test (via ear tag) of every newborn calf, or blood antibody tests of a minimum of five cattle between 9 to 18 months old from each management group[18]. In antibody testing herds, follow up tests with tissue or blood tests for antigen or virus are needed to identify any PIs[18]. Herds may also submit bulk milk test results (antigen, virus or antibody) to BVDFree in addition to the required tests. A parallel scheme (Stamp It Out) ran from 2018 to 2020 and funded farmers to test for BVD, with the option to also submit the results to BVDFree for accredited herd status[10].

Assessment of test results and demographics of farmers participating in BVDFree are needed to assess the schemes' progress and inform decisions on further development towards eradication. In this study, we present a descriptive analysis of participation and test results submitted to the BVDFree database between 2016 and 2020. We also investigate if there is evidence for specific factors to impact the likelihood of herds not continuing to submit tests to the BVDFree scheme, which may offer insights to inform strategies to enhance engagement.

Materials and methods

Ethical approval was granted by the University of Warwick Biomedical and Scientific Research Ethics Committee (BSREC 100/19-20) prior to commencement of the study.

Data source

BVDFree provided data that included all test results (535,332) submitted from samples taken between 2016 and 2020 inclusive (correct as of 14th April 2021). All herd-level information associated with each test was collected at the time the herd signed-up to BVDFree and included the County Parish Holding number, postcode, type of herd (dairy/beef breeder/beef finisher/calf rearer), herd size (number of breeding cows) and veterinary practice. Test-level information was complete for all tests and included the dates the sample was taken, tested and uploaded, the type of sample (tissue/blood/milk), whether the sample was pooled from multiple animals, the type of test used (antibody/antigen and ELISA/PCR), the laboratory and the test result. Herd-level details contained missing data; details are provided in Supplementary Table 1.

Data cleaning

We conducted all data preparation and analysis using R statistical software (version 4.0.5)[19].

Minimal data cleaning was necessary. We replaced the herd size for 27 (/5,847) herds: one herd had a range that was replaced with the midpoint, three herds had a minimum herd size which was replaced with the minimum, one herd had an implausibly large size of 9,000 which was reduced by a factor of 10 (consistent with the number of tests), and 22 beef breeder and dairy herds had herd sizes of 0 which was replaced as missing. We also replaced the sample date for 89 (/535,332) tests which had a later sample date than the automatically generated test result upload date: the 36 tests that had a sample date more than six months after the test upload date (which appeared to be due to an incorrect year) had the year changed to a date that preceded the upload date, and the sample dates of the remaining 53 tests were changed to the date of upload. We repeated all analyses with the omission of herds and tests with altered data and there were no changes in the patterns described.

Descriptive analysis

To enable identification of tests in the database that were likely to be from herds conforming to BVDFree testing requirements[18], we categorised herds according to the test regime employed in any one calendar year: antigen (only used individual antigen or virus tests) or antibody (minimum of five individual antibody tests). We then classified herds as antigen positive if at least one individual antigen or virus test was positive and antibody positive if at least one individual antibody test was positive. We investigated the testing behaviour of herds that we categorised as using either testing regime to verify that their testing behaviour appeared compliant with the required test regime. We also investigated the proportion of herds with a positive antigen test for different numbers of individual antigen tests as a proportion of their herd size, to assess the impact of using different cut-offs in our definition.

Summary statistics were calculated by test regime (antigen or antibody), herd type (beef breeder only or dairy only) and calendar year. Assessment of spatial distribution of the herds in the dataset by year was conducted by plotting herd locations by postcode. Regional variation in prevalence of herds with positive antigen or antibody test results were assessed by calculating the proportion of the antigen or antibody testing herds with a positive test result in each region of England and plotting heatmaps of the resulting prevalence.

Test regimes used by the participating farmers

Factors associated with the test regime used by each herd (antibody or antigen) were explored using a generalised logistic mixed effects model to account for herds testing for multiple years. The model was built using the lme4 package (v1.1-26)[20]. Herd size had a log-normal distribution, so we applied a natural log transformation (Supplementary Figure 1). The fixed effects tested were year of testing, herd size (natural log transformed) and herd type (beef breeder/dairy). Herd was a random effect. Terms with a P value less than 0.05 were selected in the final model. We assessed final model fit using decile plots of the observed and predicted data[21].

Continued participation of herds in the BVDFree scheme

Factors associated with the herds in the scheme each year participating again the following year were investigated using a generalised logistic mixed effects model to account for herds testing for multiple years. The model was built using the lme4 package (v1.1-26)[20] and also with a natural log transformation to herd size. The fixed effects were year of testing, herd size (natural log transformed), test regime (antigen/antibody) and herd type (beef breeder/dairy). Herd was a random effect. All terms with a P value less than 0.05 were omitted from the final model. Assessment of the final model fit was carried out using decile plots of the observed and predicted data[21].

Results

Participating herd summary statistics

A total of 5,847 herds submitted at least one test to BVDFree between 2016 and 2020 (Supplementary Figure 2), which represents approximately 15% of English cattle herds[22]. The number of herds submitting tests increased each year from 2016, peaking at 4,119 in 2019 (Supplementary Figure 2). In 2020, there were 3,555 herds submitting tests, corresponding to 60.8% of herds registered with BVDFree. The herds were associated with 267 veterinary practices in total and the number of veterinary practices participating increased year on year with all 267 submitting tests in 2020.

The median herd size between 2016 and 2020 was 183 (IQR = 120-280) and 40 (IQR = 20-70) breeding cows for dairy and beef breeding herds respectively, which is higher than the national averages[22]. There was little change in herd sizes submitting tests each year, with medians of 170 to 190 for dairy and 44 to 50 for beef breeders for 2016 to 2020. Of the 4,622 herds of known herd type, 49.5% (2,288) were beef breeders, 46.3% (2,138) were dairy, 21.6% (999) were beef finishers and 3.1% (144) were calf rearers. These numbers represent a greater proportion of dairy holdings (approximately 20%) than beef holdings (approximately 10%)[22]. In total, 72.3% (3,340) of herds were only one type of herd, and of these 51.5% (1,720) were dairy and 43.5% (1,453) were beef breeders.

Visual inspection of herd locations plotted by postcode in each calendar year showed a similar distribution to the distribution of herds nationally across all years (Supplementary Figure 3), which was similar to the national distribution of cattle holdings[23].

The number of herds recruited to the scheme for the first time each year increased each year until 2019 (2,506 herds) (Supplementary Figure 4). There were changes in the types of herds recruited each year, with the proportion of recruited herds that were dairy decreasing each year from 0.68 in 2016 to 0.46 in 2020. There was no trend in beef herd sizes by year, however there was a decrease in the median size of newly recruited dairy herds each year (except for 2016 with a median of 170 cows), falling from 200 cows in 2017 to 160 cows in 2020.

Testing regimes used by participating farmers

There were 2,360 herds that carried out antigen testing for at least one calendar year (4,082 herd-years for 2016-2020). There was a bimodal distribution to the number of tests carried out as a proportion of the number of breeding cows (used as a proxy for proportion of calves tested), with peaks at both 0.1 and 0.8 (Supplementary Figure 5). The highest peak was at 0.8 for beef breeders and 0.1 for dairy. Herds with a greater proportion of antigen tests were more likely to have a BVD positive test result. However, as there was little change in the proportion of herds positive for BVD when varying the cut-off for the number of tests as a proportion of herd size between 0.1 and 0.6 (Supplementary Figure 6), we included all herds in estimates of prevalence (see below).

There were 3,162 herds that tested using blood antibody tests for at least one year (4,522 herd-years for 2016-2020). Antibody testing herds had a median of 1 test visit per year (range = 1-4 for beef breeders and 1-3 for dairy herds). Fifty-one percent of antibody testing herds with a positive result also carried out individual antigen tests in the same year.

The generalised logistic mixed-effects model of variables associated with antigen versus antibody testing indicated that herds were more likely to antibody test in 2018 to 2020 than in 2016 and 2017 (Table 1). Dairy herds were more likely to antigen test than beef breeder herds (odds ratio = 7.14, 95% confidence interval = 4.46-11.41). Herd size was not selected in the final model. Model fit was deemed adequate (Supplementary Figure 7).

Prevalence of antigen or antibody positive herds

In 2020, 13.5% of beef breeding herds were antigen (8.3%) or antibody (17.0%) positive (had at least one positive individual antigen or individual antibody test respectively) compared to 20.0% of dairy herds (20.6% antigen positive, 19.2% antibody positive). There were fluctuations in the prevalence of positive herds between years with no clear trend (Figure 1). Among antigen testing herds, there was a higher prevalence of herds with positive test results in dairy herds than beef breeder herds, but no difference for antibody testing herds (Figure 1). There were also differences in the prevalence of antigen or antibody positive herds by region between years (Figure 2). There were low numbers of farmers in some regions for the early years of the BVDFree scheme, resulting in very wide confidence intervals, therefore only the most recent years are shown.

Prevalence of antigen positive tests

A total of 0.4% of tests submitted by antigen testing herds in 2020 were positive, which was less than during the 2016 to 2019 period where between 0.5% to 1% of tests submitted by antigen testing herds were positive (Figure 3). Within antigen positive herds, 1.5% of tests submitted were positive in 2020, which was also less than that throughout 2016 to 2019 (Figure 3). However, as for herd-level prevalence of positive tests, the animal-level prevalence fluctuated between years with no clear trend.

Prevalence of antibody positive tests

A total of 9.2% of tests submitted by antibody testing herds in 2020 were positive, which was less than during the 2016 to 2019 period where between 9.5% to 14.3% of tests submitted by antibody testing herds were positive (Figure 4). Within antibody positive herds, 38.9% of tests submitted were positive in 2020, compared to 32.4% to 41.3% throughout 2016 to 2019 (Figure 4). There was also no clear temporal trend in the proportion of tests that were positive.

Continued participation of herds in the scheme

In the generalised logistic mixed effects model of factors associated with herds continuing to participate the following year, herds were more likely to continue: the greater the number of years they had already submitted tests, the greater the number of years with a positive result and the greater the number of breeding cows. Herds were also more likely to submit tests the following year in 2017 and 2018 than 2016 or 2019 and if they tissue antigen tested instead of blood antibody tested (Table 2). There was no association with herd type. Model fit was deemed adequate (Supplementary Figure 8).

Discussion

In this paper we present an analysis of the voluntary BVDFree England scheme dataset of test results, to assess current infection status, to investigate the temporal trends in participation and to identify associations between herd characteristics and the presence of BVD infection. Between 2016 and 2019 there was an increasing trend in the number of participating herds, with a small drop in the number of participating herds in 2020. Herd-level prevalence was generally higher in dairy herds than beef breeder herds, but this differed by test regime used. We also identified a higher likelihood of participating again in the following year with increasing herd size, in certain years and if a positive result had been previously reported for that herd.

A total of 13% of beef breeder herds were antigen or antibody positive in 2020, compared to 20% of dairy herds. This is higher than the overall estimates of BVD prevalence of 11% in Northern Ireland and Ireland at the start of the compulsory phases of their schemes[13,15,24], but similar to the prevalence in Ireland in 2012 at the beginning of their voluntary phase (12% for beef, 18% for dairy)[25]. Our estimates are lower than the estimated 26% of herds that are BVD positive in Wales, which is also still in the voluntary phase of its eradication programme but has recruited approximately 80% of herds[22,26]. Previous research found a lower prevalence of BVD in dairy herds in England than in Wales[27]. Scotland's estimated prevalence of BVD positive herds at the start of their compulsory phase was 40%, however this included herds that did not comply with testing therefore the true prevalence is likely to have been lower[12]. These prevalence estimates (except for Wales) include all farms, however due to the voluntary nature of the BVDFree scheme the estimates here are from a sample of cattle herds and there is likely to be a bias in the farmers who join the scheme. The regression model investigating factors associated with herds continuing participation in the following year suggested that herds that had positive test results were more likely to stay in the scheme. BVD positive herds are more likely to be BVD positive in the future[24] and this, in addition to the larger herd size of participating herds, suggests that the prevalence of BVD positive herds in England may well be lower than estimated here. In Northern Ireland there was a higher prevalence of BVD in the herds participating in the voluntary phase than when testing became mandatory for all herds[24].

There was no clear trend in the prevalence of antigen or antibody positive herds, which fluctuated by year. The fluctuations could result from the large number of farmers recruited to the scheme in 2019 who had not engaged with the scheme previously, and therefore may have been less likely to be controlling BVD (Supplementary Figure 4), and changes in the farmers participating between years. Dairy herds usually had a higher prevalence of BVD test positive herds in each year than beef breeder herds, which is common in the literature[9,15,28]. However, the difference we identified is lower than that found in other studies[9], even for 2020 which had the largest difference in prevalence of positive tests between herd types. Dairy herds are expected to have a higher prevalence of BVD than beef herds due to the larger sizes of dairy herds increasing the transmission of infection (both larger herds and dairy herds are more likely to be BVD positive[24,29,30]), or due to the increased mixing of cows within dairy herds compared to beef herds.

There were fewer antigen positive cattle in a herd in 2020 than the previous four years, with 0.4% of cattle in antigen testing herds positive for BVD. There was also a lower proportion of cattle positive for BVD antigen in antigen positive herds in 2020 (1.5%) than the previous four years. This test positive rate is similar to other European countries, which typically have a BVD prevalence of less than 0.8% of animals[9], and lower than Northern Ireland where 0.6% of calves were PIs in the first year of their compulsory phase[28]. Similarly, 0.5% of calves in Ireland were antigen positive at the start of their voluntary phase[25]. We were unable to identify transiently infected cattle in the dataset because we did not have animal identification data to link an animal to a test. In Ireland, 83% of antigen positive calves were confirmed to be PIs[25]. Therefore, the actual PI rate may be lower than this estimate. There are typically low numbers of PI calves per positive herd, with only one PI detected in 66% to 71% of BVD infected herds in Ireland and Northern Ireland[25,28].

Dairy herds were more likely to use antigen testing than beef herds, and all herds were more likely to use antibody testing in 2018 to 2020 than in 2016. "Stamp It Out" funding was available to vets to carry out blood antibody testing from 2018 to 2021, which could have encouraged farmers to use antibody testing during those years. Dairy herds, being larger, are both the most likely to have sufficient youngstock numbers for blood antibody cohort testing and likely to find antibody testing more cost effective[31,32]. However, dairy herds may also be more limited in the choice of test, with calves not necessarily being retained on the farm past nine months old making blood cohort antibody testing unfeasible. Blood antibody testing must be carried out once calves are old enough (no younger than six months old) to avoid false positives from maternal antibodies, whereas tissue antigen testing can be carried out on calves of any age[33]. Antigen testing dairy herds were more likely to be positive than antigen testing beef breeder herds. It is possible that beef and dairy herds choose which test type to use for different reasons. Dairy herds have the option of bulk milk testing for BVD antigen or antibodies, and it is possible that herds that already suspect they might have BVD through their bulk milk results use antigen testing to directly identify the PI calves.

Herds that join the scheme do not always continue submitting tests in following years. Continued submission of tests to the scheme was associated with years in which funding was available for testing, using antigen testing, large herds and being antigen or antibody positive in a previous year. Increase in participation coinciding with available funding is common to other BVD control schemes[34]. The cost effectiveness of testing for BVD is lower in herds that do not have BVD[12] and who are not experiencing production losses from BVD infection, which may explain why farmers with negative test results are less likely to test the following year. Increased demand from buyers for BVD-free accredited stock would help increase the benefits of testing to BVD-free farmers. Antibody testing is more cost-effective in larger herds since they have greater numbers of youngstock per management group, and this finding has also been identified in other voluntary BVD schemes[35], which may explain the overrepresentation and increased continued participation of larger herds to the scheme. Antigen testing herds were more likely to stay engaged with the BVDFree scheme than those using antibody testing. Often a tissue tag test is incorporated into the individual animal identification tag which all calves require by law, therefore tissue antigen testing easily fits into the farmers routine which could be one possible explanation. The need for research into ways of improving farmer engagement with BVD control has been identified previously[36]. Most farmers join health schemes for the benefits to themselves rather than contributing to national disease control[34]. This issue is also compounded by the fact that not all BVD-engaged herds submit tests to BVDFree because there are other accreditation schemes available.

A limitation with this study is that participating farmers are unlikely to be a representative sample of English cattle farmers, which is partially evidenced in the differences in herd sizes and types recruited to the scheme each year - herds in the scheme were 1.5 to 2 times larger than average[22]. We do not know the rationale farmers have for joining the scheme. Research into the motivations of farmers to join a voluntary regional BVD scheme found no clear common reason, other than on veterinary advice[35]. Dairy farmers are over represented in the dataset, which is similar to during the voluntary phase in Ireland[25]. It was not possible to ascertain from the dataset if farmers were following the BVDFree testing requirements correctly (that is tissue testing every calf, or antibody testing the correct number of youngstock of the correct age per management group), and therefore what BVD status they would have been assigned by their vet from their test results. Additionally, we do not know the identification numbers of tested animals, and therefore which animals were suspected as being transiently infected and therefore retested. This information would be a valuable addition to this analysis. Finally, these findings reflect the specific funding, testing and support landscape for BVD control in England, however some of the findings may be generalisable to other countries with voluntary schemes.

In conclusion, we have presented an estimate of the prevalence of BVD in England from a national dataset and find that although the prevalence of BVD positive tests was lower in 2020 than previous years, there was not a clear decreasing trend over that time frame. Herds with positive BVD tests, using antigen testing and larger herds were more likely to stay engaged with the scheme by testing in a following year. More widespread farmer engagement appears crucial for the effective control of BVD in England and research to stimulate this may be worthwhile.

Acknowledgements

We would like to thank all the veterinarians and farmers that submitted tests to BVDFree.

Data availability statement

Restrictions apply to the availability of this data and interested parties should get in contact with BVDFree England. The data analysis code is available on request.

Funding and competing interests statement

DA and LG are directly involved in the delivery of the BVDFree programme. NSP, EMH, MJT, MJK, JK, EF and MJG were supported by the Biotechnology and Biological Sciences Research Council (grant numbers BB/5016341/1 and BB/S01750X/1). MJT and MJK were also supported by the Engineering and Physical Sciences Research Council through the MathSys CDT (grant number EP/S022244/1). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

References

1 Houe H. Epidemiological features and economical importance of bovine virus diarrhoea virus (BVDV) infections. *Vet Microbiol* 1999;64:89-107
2 Burgstaller J, Obritzhauser W, Kuchling S, et al. The effect of bovine viral diarrhoea virus on fertility in dairy cows: two case-control studies in the province of Styria, Austria. *Berl Munch Tierarztl Wochenschr* 2016;129:103-110
3 Peterhans E, Jungi TW, Schweizer M. BVDV and innate immunity. *Biologicals* 2003;31:107-111

4 Ruminant Health & Welfare. Bold plans to eradicate BVD and sheep scab by 2031. 2021. https://ruminanthw.org.uk/2021/07/12/bold-plans-to-eradicate-bvd-and-sheep-scab-by-2031/ (accessed 7 October 2021)

5 Moennig V, Becher P. Control of Bovine Viral Diarrhea. *Pathogens* 2018;7:29

6 Presi P, Heim D. BVD eradication in Switzerland - A new approach. *Vet Microbiol* 2010;142:137-142

7 Lindberg ALE, Alenius S. Principles for eradication of bovine viral diarrhoea virus (BVDV) infections in cattle populations. *Vet Microbiol* 1999;64:197-222

8 Fulton RW, Hessman BE, Ridpath JF, et al. Multiple diagnostic tests to identify cattle with bovine viral diarrhea virus and duration of positive test results in persistently infected cattle. *Canadian Journal of Veterinary Research-Revue Canadienne De Recherche Veterinaire* 2009;73:117-124

9 Scharnbock B, Roch FF, Richter V, et al. A meta-analysis of bovine viral diarrhoea virus (BVDV) prevalences in the global cattle population. *Sci Rep* 2018;8:14420

10 Armstrong D, Gow L. Is the end in sight of bovine viral diarrhoea virus, or is it just a mirage? *Livestock* 2021;26:220-226

11 Scottish Government. Scottish BVD Eradication Scheme: guidance. 2019. https://gov.scot/publications/scottish-bvd-eradication-scheme/pages/overview/ (accessed 15 September 2021)

12 Haw R. Estimating the Savings to Farmers from Eradicating BVD. Scottish Government, 2019.

13 Animal Health & Welfare NI. Statistics update for the BVD Programme (compulsory phase). 2021. http://animalhealthni.com/page.aspx?page_id=39 (accessed 28 June 2021)

14 Animal Health & Welfare Wales. Animal Health & Welfare Wales, Gwaredu BVD. 2021. https://ahww.cymru/en/home/ (accessed 15 September 2021)

15 Graham D, More SJ, O'Sullivan P, et al. The Irish Programme to Eradicate Bovine Viral Diarrhoea Virus-Organization, Challenges, and Progress. *Frontiers in Veterinary Science* 2021;8:674557

16 Animal Health Team - Regulation Directorate. BVD Statistics. 2021. https://gov.im/categories/business-and-industries/agriculture/cattle/bovine-virus-diarrhoea-bvd-control-strategy/bvd-statistics/ (accessed 4 October 2021)

17 BVDFree. BVDFree. 2021. https://bvdfree.org.uk/ (accessed 6 August 2021)

18 BVDFree. About the scheme. 2021. https://bvdfree.org.uk/the-scheme/#testings (accessed 25 August 2021)

19 R Core Team (2021) R: A language and environment for statistical computing. 4.0.5 edn. Vienna, Austria, R Foundation for Statistical Computing

20 Bates D, Maechler M, Bolker B, et al. Fitting linear mixed-effects models using lme4. *Journal of Statistical Software* 2015;61:1-48

21 Hosmer DW, Lemeshow S. Goodness of fit tests for the multiple logistic regression-model. *Communications in Statistics Part a-Theory and Methods* 1980;9:1043-1069

22 Agriculture & Horticulture Development Board. The UK Cattle Yearbook 2019. 2019.

23 Animal & Plant Health Agency: Livestock Demographic Data Group. Cattle population report: Livestock population density maps for GB. 2020.

24 Charoenlarp W, Frankena K, Strain SAJ, et al. Spatial and risk factor analysis of bovine viral diarrhoea (BVD) virus after the first-year compulsory phase of BVD eradication programme in Northern Ireland. *Prev Vet Med* 2018;157:34-43

25 Graham DA, Lynch M, Coughlan S, et al. Development and review of the voluntary phase of a national BVD eradication programme in Ireland. *Vet Rec* 2014;174:67

26 Paton N. Getting momentum to progress from a voluntary to a compulsory eradication programme. In: BVDzero Congress; 7 July 2021, Online, 2021

27 Velasova M, Damaso A, Prakashbabu BC, et al. Herd-level prevalence of selected endemic infectious diseases of dairy cows in Great Britain. *J Dairy Sci* 2017;100:9215-9233

28 Animal Health & Welfare NI. The Northern Ireland BVD Eradication Programme: A Review of Year One. 2017.

29 Barrett D, Clegg T, McGrath G, et al. Herd-level factors associated with detection of calves persistently infected with bovine viral diarrhoea virus (BVDV) in Irish cattle herds with negative herd status (NHS) during 2017. *Prev Vet Med* 2020;179:104990

30 van Roon AM, Mercat M, van Schaik G, et al. Quantification of risk factors for bovine viral diarrhea virus in cattle herds: A systematic search and meta-analysis of observational studies. *J Dairy Sci* 2020;103:9446-9463

31 Tratalos JA, Thulke HH, Graham DA, et al. Decision support beyond total savings - Eligibility and potential savings for individual participants from changes in the national surveillance strategy for bovine viral diarrhoea (BVD) in Ireland. *Prev Vet Med* 2018;155:38-44

32 Thulke HH, Lange M, Tratalos JA, et al. Eradicating BVD, reviewing Irish programme data and model predictions to support prospective decision making. *Prev Vet Med* 2018;150:151-161

33 McDougall S. Effect of calf age on bovine viral diarrhea virus tests. *J Vet Diagn Invest* 2021;33:528-537

34 Heffernan C, Azbel-Jackson L, Brownlie J, et al. Farmer attitudes and livestock disease: exploring citizenship behaviour and peer monitoring across two BVD control schemes in the UK. *PLoS One* 2016;11:e0152295

35 Azbel-Jackson L, Heffernan C, Gunn G, et al. Exploring the role of voluntary disease schemes on UK farmer bio-security behaviours: Findings from the Norfolk-Suffolk Bovine Viral Diarrhoea control scheme. *PLoS One* 2018;13:e0179877

36 Evans CA, Pinior B, Larska M, et al. Global knowledge gaps in the prevention and control of bovine viral diarrhoea (BVD) virus. *Transbound Emerg Dis* 2019;66:640-652

Tables

Table 1. Results of a generalised logistic mixed-effects model to identify factors associated with antigen testing (compared with antibody testing) for bovine viral diarrhoea in 2,749 cattle herds from 2016 to 2020 (a total of 5,146 herd-years).

Fixed effects		N	%	OR	95% CI	P value
Year of test:	2016	189	3.7	1.00		
	2017	513	10.0	0.73	0.35 – 1.51	0.392
	2018	892	17.3	**0.24**	**0.12 – 0.48**	**< 0.001**
	2019	1,765	34.3	**0.04**	**0.02 – 0.08**	**< 0.001**
	2020	1,787	34.7	**0.29**	**0.15 – 0.58**	**< 0.001**
Herd type:	Beef	2,596	50.4	1.00		
	Dairy	2,550	49.6	**7.14**	**4.46 – 11.41**	**< 0.001**

N = number of herd/year combinations, % = percent of herd/year combinations, OR = odds ratio, 95% CI = Wald's 95% confidence interval. Significant terms (P<0.05) are in bold

Table 2. Results of a generalised logistic mixed-effects model to identify factors associated with not submitting (as opposed to submitting) bovine viral diarrhoea tests to BVDFree the following year from 2016 to 2019 in 2,224 cattle herds (a total of 3,359 herd-years).

Fixed effects		N	%	OR	95% CI	P value
Number of years submitting tests		3,359	100.0	**0.51**	**0.45 – 0.58**	**<0.001**
Proportion of years positive		3,359	100.0	**0.75**	**0.61 – 0.93**	**0.010**
Herd size (ln)		3,359	100.0	**0.81**	**0.75 – 0.87**	**<0.001**
Year:	2016	189	5.6	1.00		
	2017	513	15.3	**0.47**	**0.32 – 0.70**	**<0.001**
	2018	892	26.6	**0.47**	**0.33 – 0.68**	**<0.001**
	2019	1,765	52.5	0.91	0.64 – 1.29	0.587
Type of testing:	Antibody	1,915	57.0	1.00		
	Antigen	1,444	43.0	**0.41**	**0.34 – 0.50**	**<0.001**

N = number of herd/year combinations, % = percent of herd/year combinations, OR = odds ratio, 95% CI = Wald's 95% confidence interval. Significant terms (P<0.05) are in bold

Figures

Figure 1: Percentage of antibody or antigen testing beef breeder herds (red circles) or dairy herds (blue triangles) positive for bovine viral diarrhoea antibody or antigen with binomial 95% confidence interval error bars.

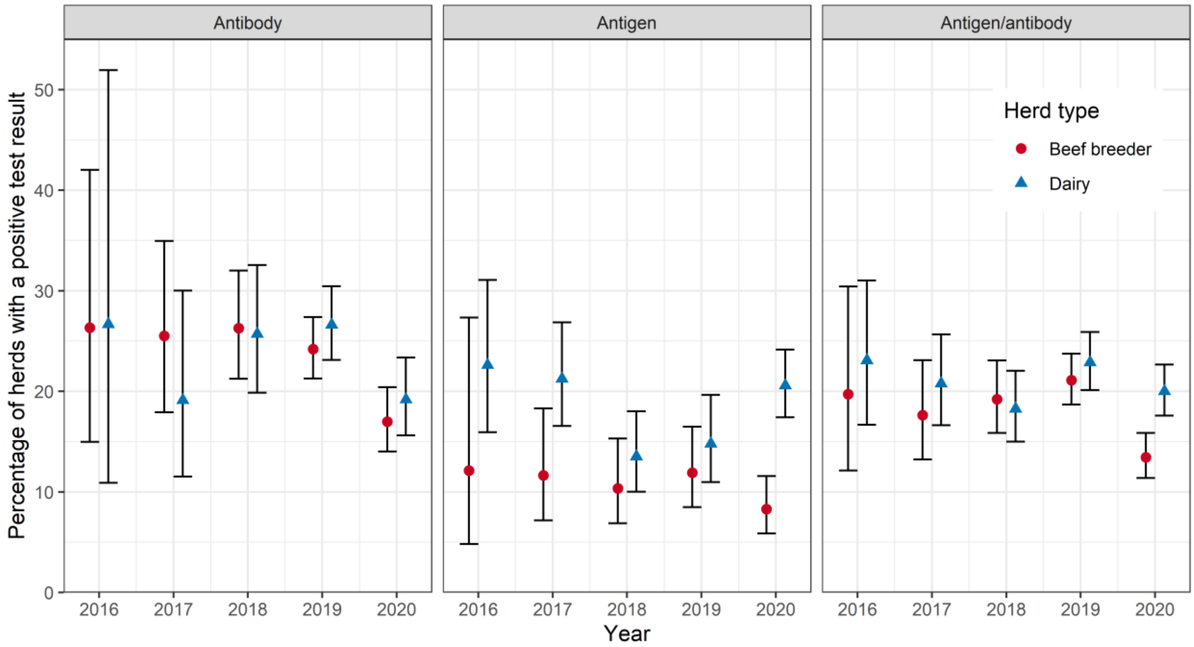


Figure 2: Proportion of beef breeding and dairy herds in each region of England testing positive for bovine viral diarrhoea (BVD) antigen or antibody in 2019 and 2020, with binomial 95% confidence intervals below. Darker red shading corresponds to a higher proportion of herds testing positive for BVD antigen or antibody.

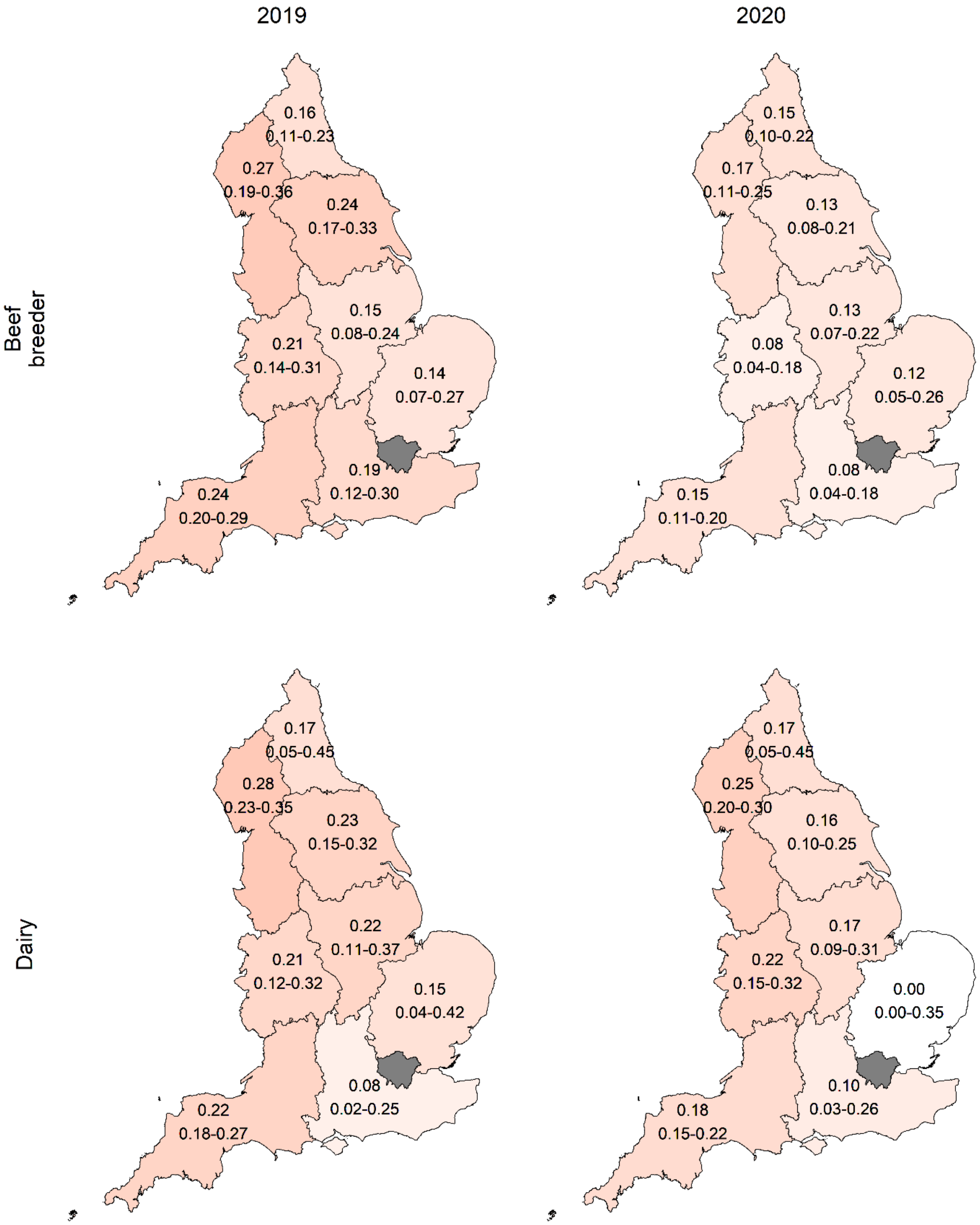


Figure 3: Percentage of individual bovine viral diarrhoea antigen tests returning a positive result for all antigen testing herds (red triangles) and antigen positive herds (blue circles) each calendar year with binomial 95% confidence interval error bars.

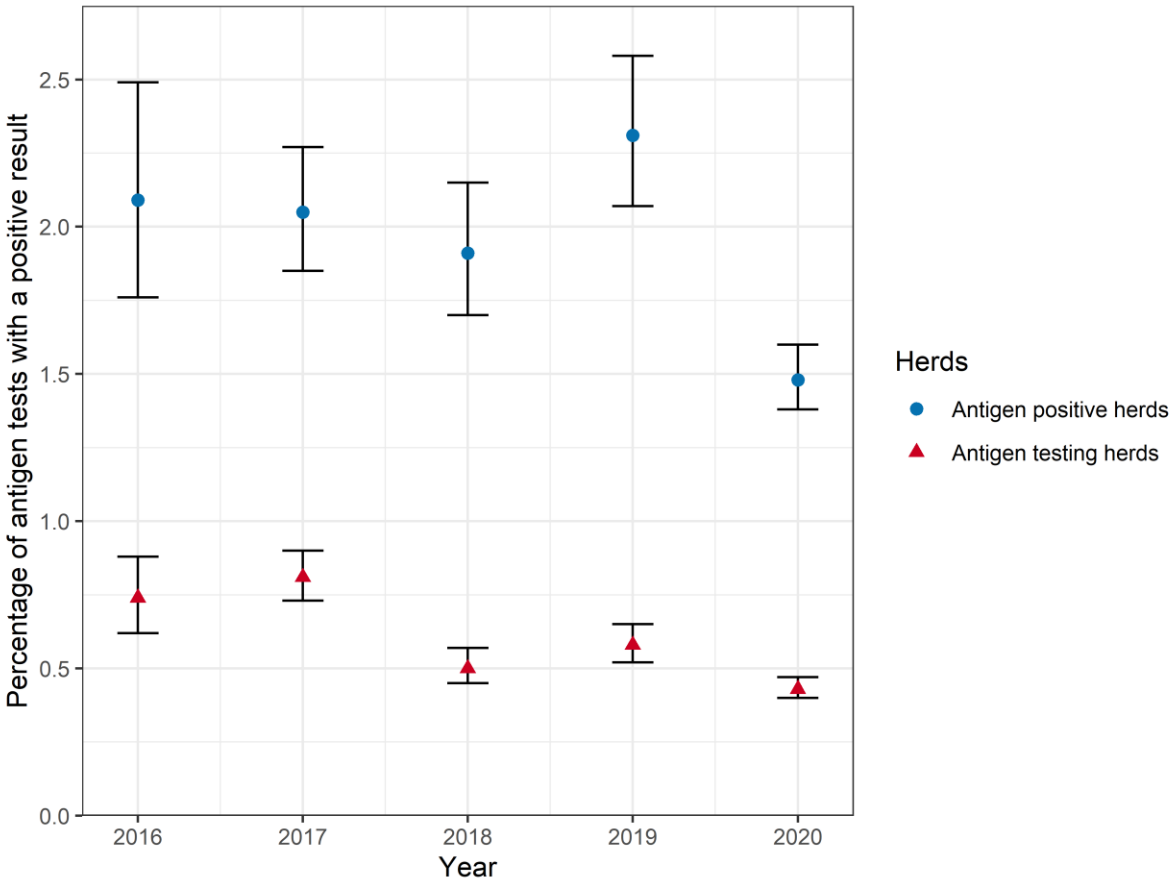
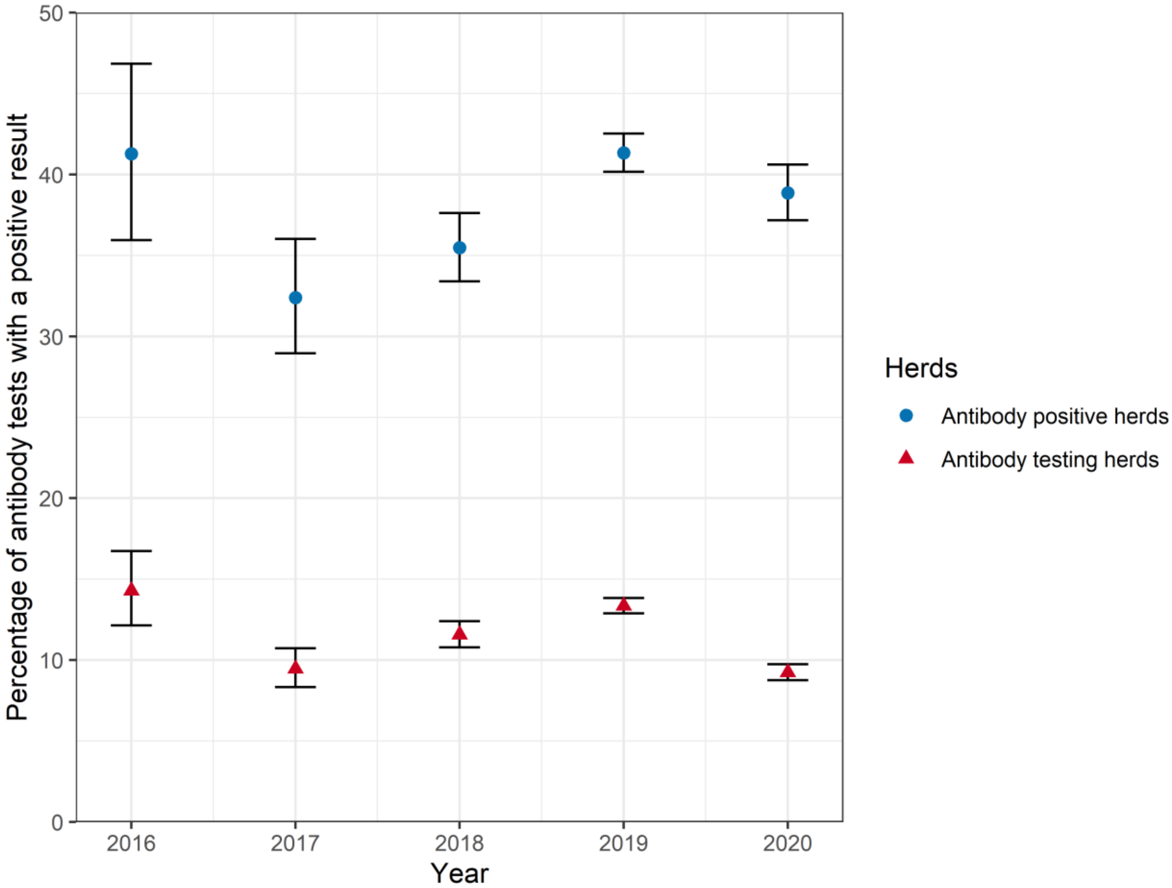


Figure 4: Percentage of individual bovine viral diarrhoea antibody tests returning a positive result for all antibody testing herds (red triangles) and antibody positive herds (blue circles) each calendar year with binomial 95% confidence interval error bars.

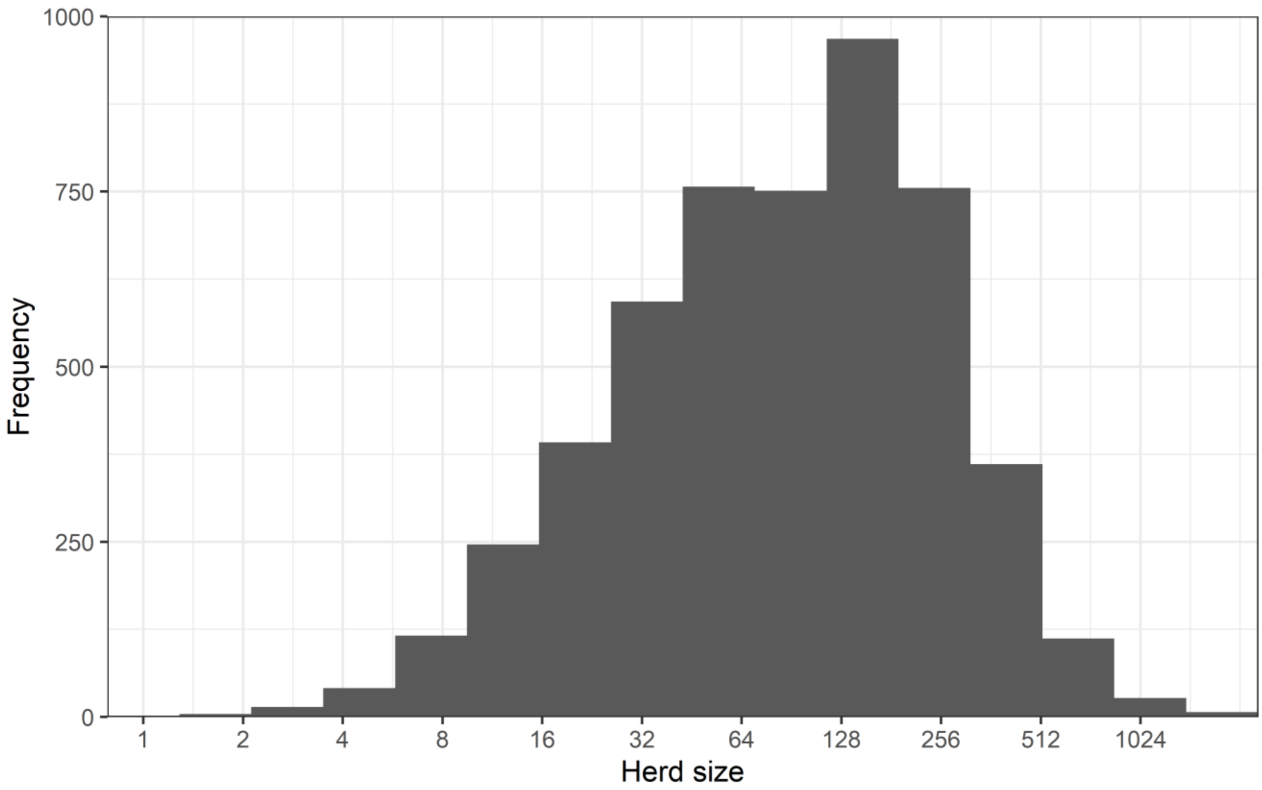


Supplementary Information

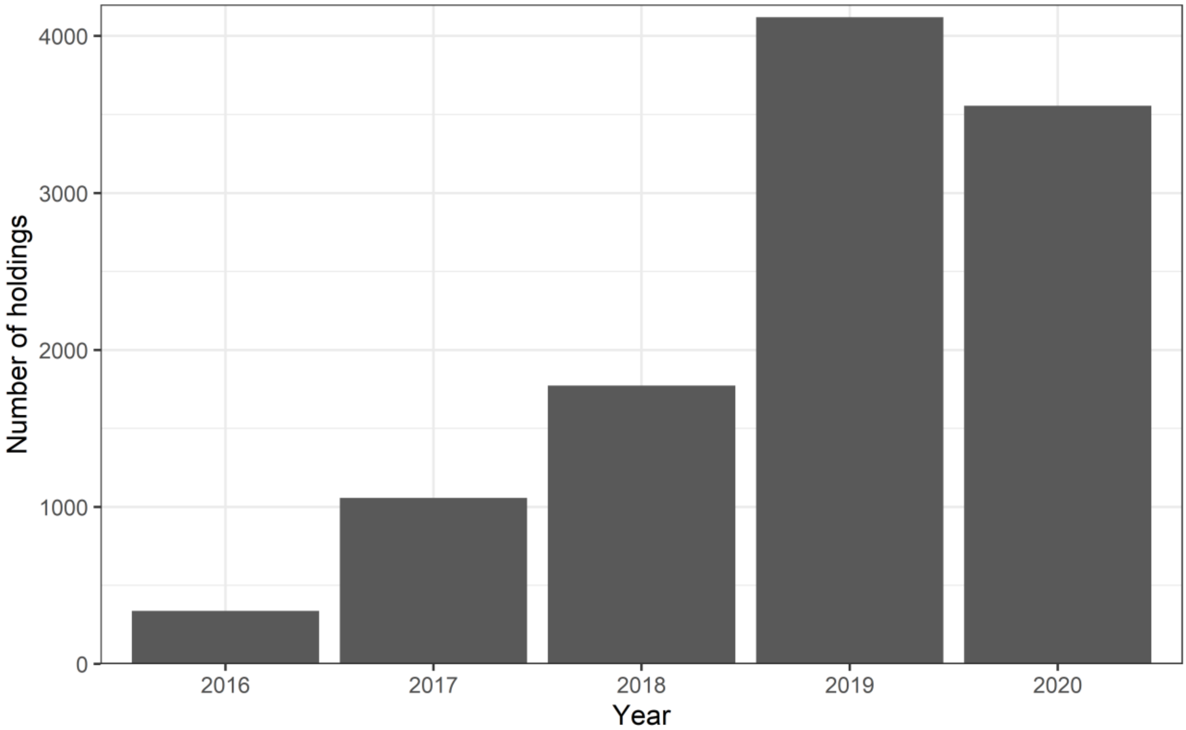
Supplementary Table 1. The number of tests with missing data for each herd-level factor.

Type of data	Number of tests with missing data
County Parish Holding number	5
Postcode	49,402
Type of herd	58,678
Herd size	64,242
Veterinary practice	49,529

Supplementary Figure 1. Histogram of the natural log transformed herd size for 5,146 herd/calendar year combinations for beef breeder or dairy herds using an antigen or antibody testing regime.

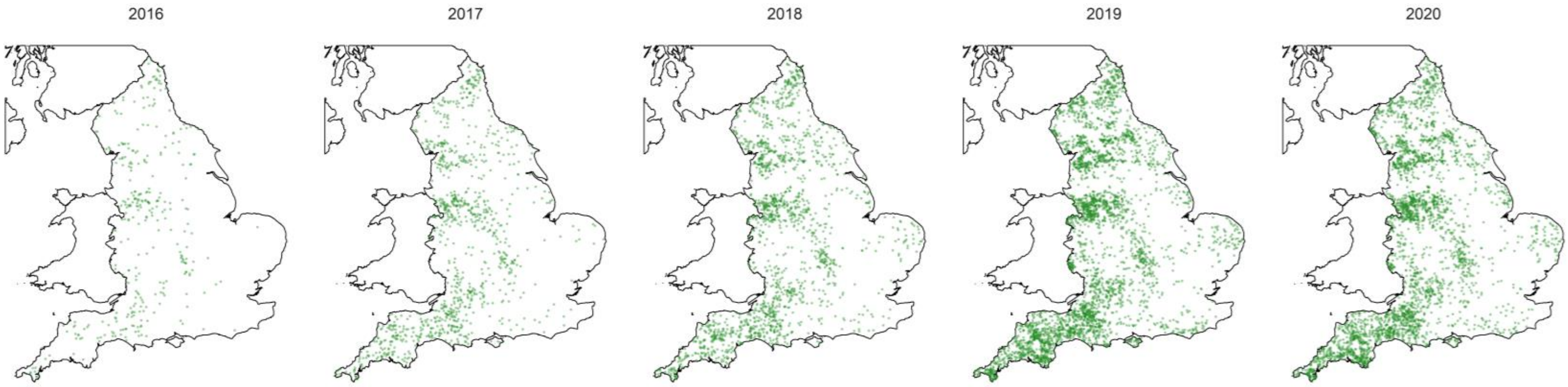


447 *Supplementary Figure 2: Number of holdings submitting tests results to BVDFree per calendar year.*
448 *There are 5,847 holdings represented in total.*

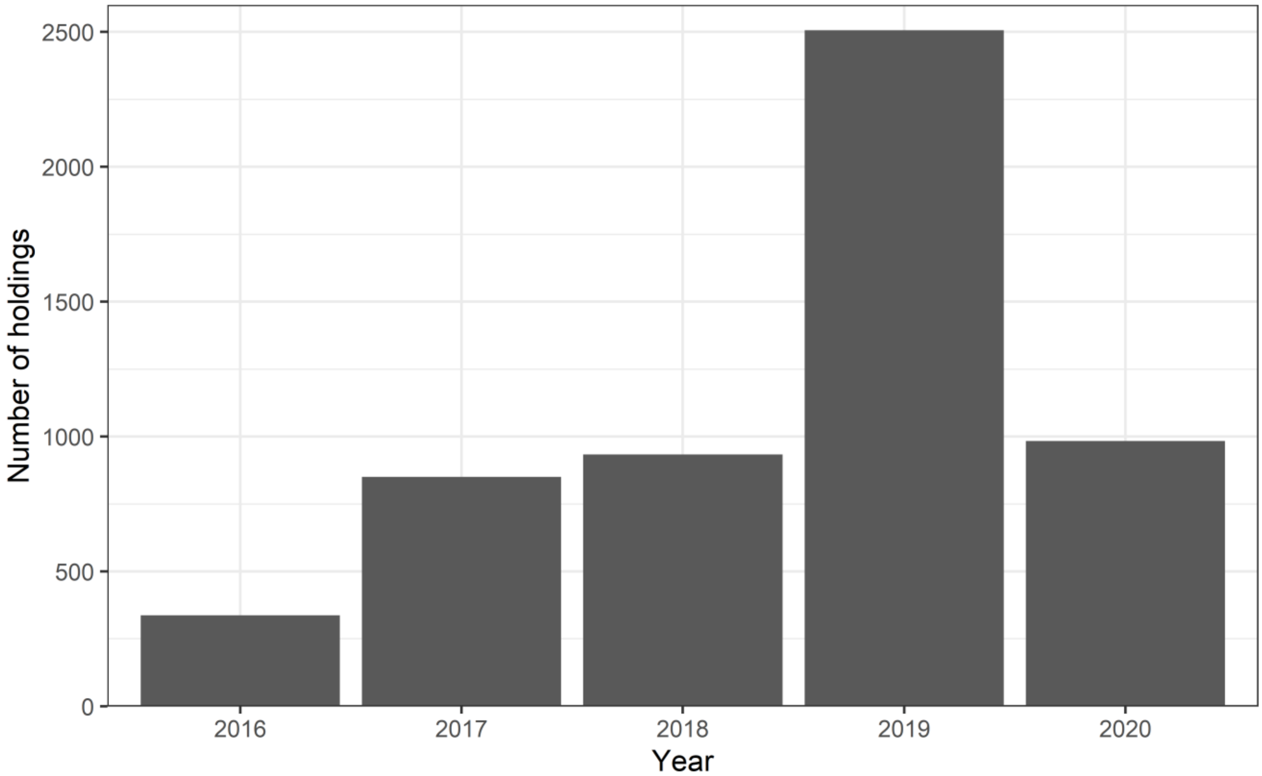


449

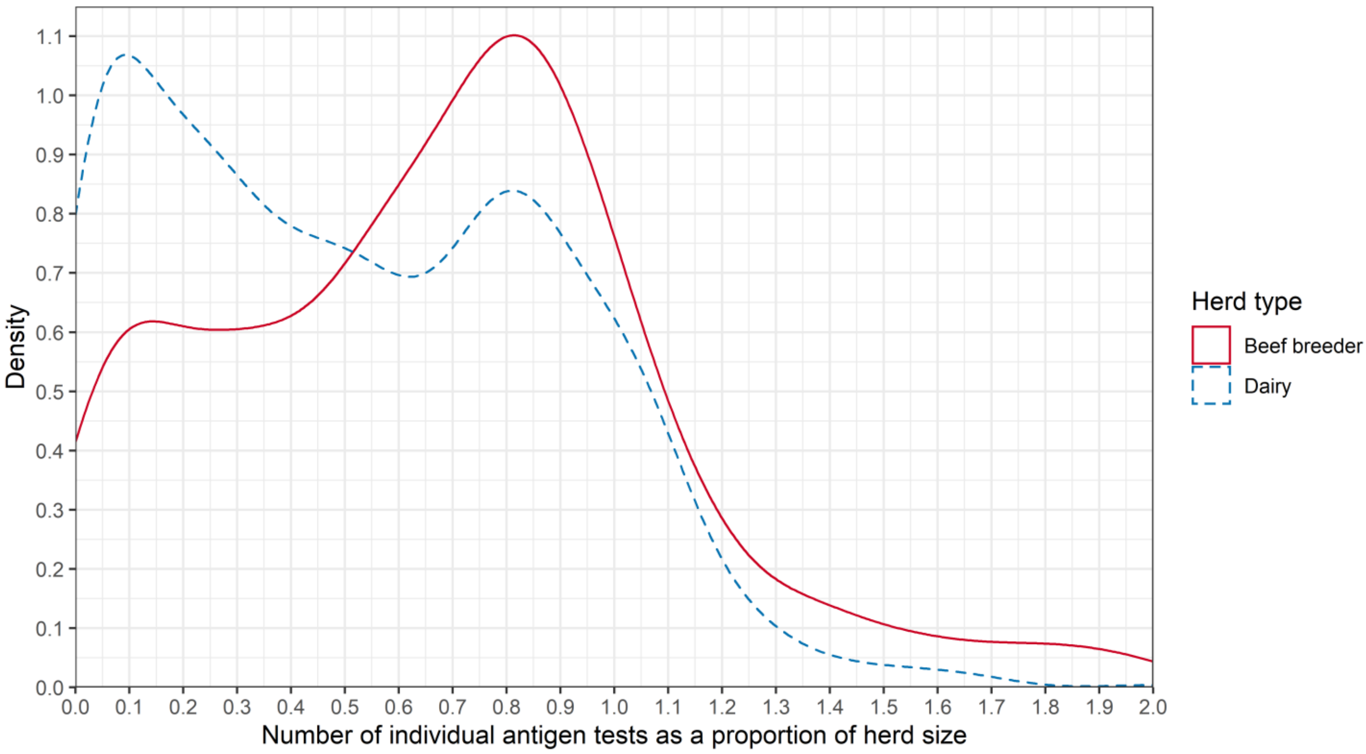
450 *Supplementary Figure 3: Locations of herds submitting tests to BVDFree each year for 2016 to 2020.*



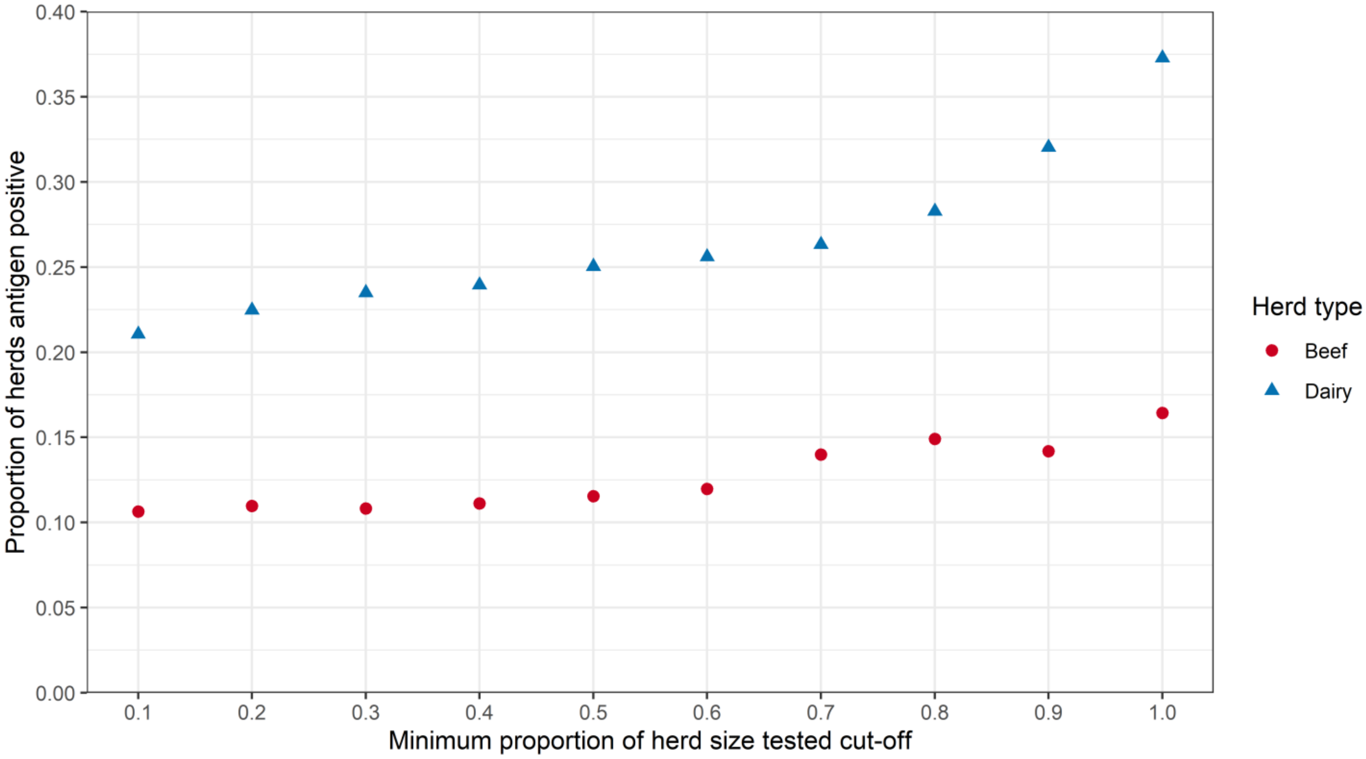
Supplementary Figure 4: Number of holdings recruited to BVDFree for the first time per year. There are 5,847 holdings in total.



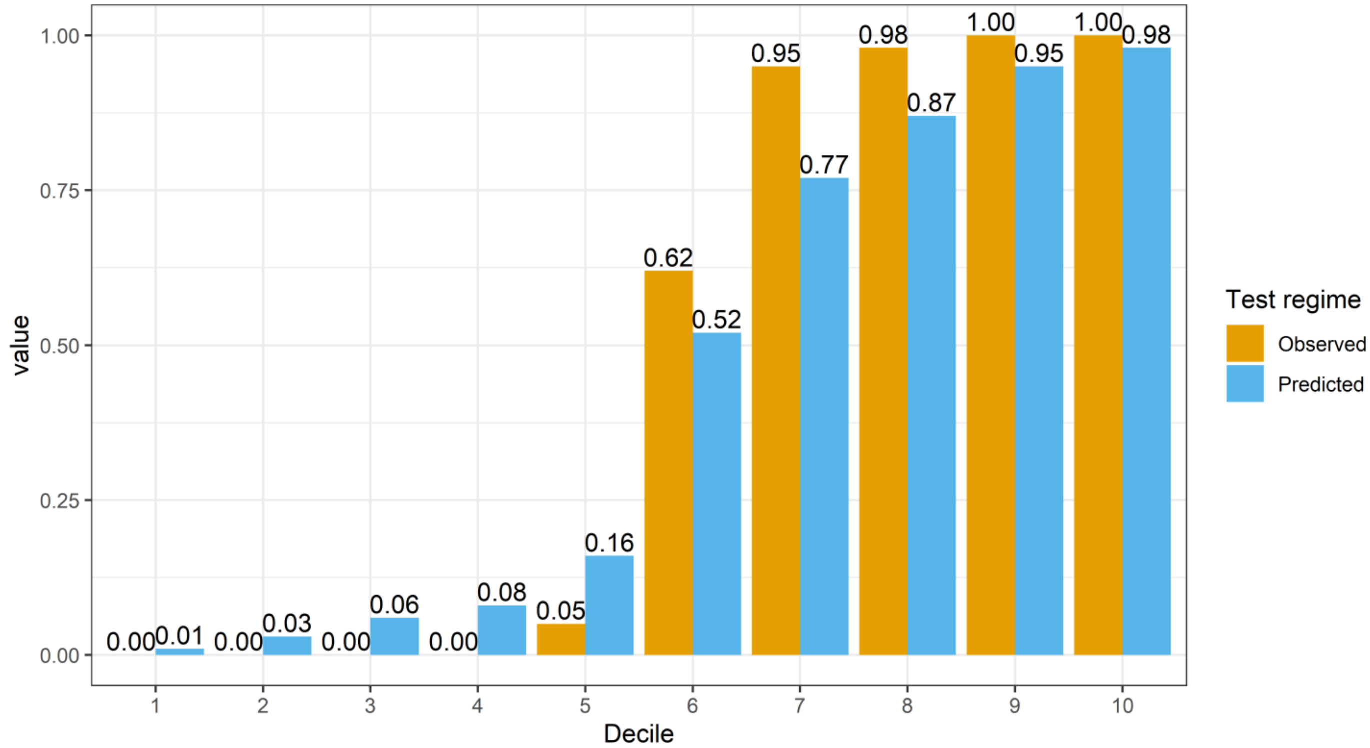
Supplementary Figure 5: Number of individual tests carried out by antigen testing herds as a proportion of herd size for beef breeding (red solid line) and dairy herds (blue dashed line).



Supplementary Figure 6: Proportion of antigen testing herds that were positive for BVD at different cut-offs for the minimum proportion of the herd tested for beef breeder herds (red circles) and dairy (blue triangles).



Supplementary Figure 7: Decile plot of the fit of a generalised logistic mixed-effects model explaining antigen versus antibody test regime for 2,749 herds from 2016 to 2020, with 5,146 herd-years. Orange bars correspond to the observed data and blue bars correspond to the predictions from the generalised logistic mixed-effects model.



Supplementary Figure 8: Decile plot of the fit of a generalised logistic mixed-effects model explaining herds not submitting BVD tests the following year for 2,224 herds from 2016 to 2019, with 3,359 herd-years. Red bars correspond to the observed data and blue bars correspond to the predictions from the generalised logistic mixed-effects model.