Enhancing the use of data for the scanning surveillance of sheep scab as a model for endemic diseases

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Abstract

Scanning surveillance facilitates the monitoring of many endemic diseases in Great Britain, including sheep scab, an ectoparasitic disease of major economic and welfare burden. With emerging antiparasitic resistance making the development of control strategies particularly timely, this thesis aimed to enhance the use of data for the scanning surveillance of sheep scab, specifically to guide future control strategies. In Chapter 2 an existing source of scanning surveillance, positive skin scrape diagnoses ('positive scrapes') reported in the Veterinary Investigation Diagnosis Analysis (VIDA) database, were analysed to identify "hotspots" of disease for targeted control and evaluate a potential denominator to improve the interpretation of the count of positive scrapes. The details of all past targeted disease control initiatives were also collated and a temporal aberration detection algorithm (TADA) was applied to investigate their impact on positive scrape diagnoses. Then, in Chapter 3, data from a recently commercialised diagnostic test, the sheep scab ELISA, were collected and analysed, to explore its current use and uptake since commercialisation, identify risk factors for infestation and to consider its value as a complementary source of scanning surveillance. The results of this study showed a decline in positive scrapes, however, the positive scrapes as a proportion of submissions had remained stable. A strong seasonal pattern with high counts in winter was also observed. Wales was identified as a particular "hotspot", with the highest count of positive scrapes. Furthermore, two potential denominators 'scheduled scrapes' and 'skin submissions' were identified to provide further interpretation of positive scrapes. Finally, 11 disease control initiatives were identified and collated, and the TADA offered a framework to objectively measure the impact of these, showing 'free testing' initiatives had the most impact on positive scrape diagnoses. The sheep scab ELISA demonstrated a steady uptake since the beginning of testing, an established seasonal pattern and broad spatial uptake across England and Wales, with few submissions originating from Scotland. The recommended 12-sample submissions for monitoring were most frequently submitted; however, the majority of submissions originated from itchy sheep, showing this test is also widely used to diagnose sheep with clinical or subclinical signs. For the first time, double fencing was shown to significantly decrease the likelihood of a positive serostatus submission; however, common grazing was not identified as a risk factor. Ultimately, this project resulted in the creation of a new data source that could enhance the scanning surveillance of sheep scab. Using sheep scab as a model, the methods used here offer a framework to improve the use of existing and new data sources for the scanning surveillance of other endemic diseases.

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Author's Declaration

I, Eilidh Geddes, declare that, except where explicit reference is made to the contribution of others, that this thesis is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

Eilidh Geddes

Abbreviations

ADAS	Agricultural Development Advisory Service
AHDB	Agriculture and Horticulture Development Board
AHS	Animal health surveillance
AHSURED	Animal Health Surveillance reporting guidelines
APHA	Animal and Plant Health Agency
Biobest	Biobest Laboratories Ltd
CDC	Centers for disease control and prevention
DEFRA	Department for Environment, Food and Rural Affairs
DSC	Disease Surveillance Centre
ELISA	Enzyme-linked Immunosorbent Assay
EU	European Union
GB	Great Britain
HCC	Hybu Cig Cymru
NUTS	Nomenclature of Territorial Units for Statistics
ML	Macrocyclic lactone
MRI	Moredun Research Institute
OD	Optical Density
ONS	Office for National Statistics
OP	Organophosphate
RAMA	Registered animal medicines advisor
RDPE	Rural development programme for England
SRUC VS	Scotland's Rural College Veterinary Services
SSSI	Scottish Sheep Scab Initiative
TADA	Temporal aberration detection algorithm
UK	United Kingdom
UKAS	United Kingdom Accreditation Service
USA	United States of America
VIC	Veterinary Investigation Centre
VIDA	Veterinary Investigation Diagnosis Analysis
VIO	Veterinary Investigation Officer
VMD	Veterinary Medicines Directorate

1. Introduction

Endemic diseases, which are widely accepted in modern livestock farming, pose a significant challenge to livestock health, welfare and productivity and often have serious implications for public health and food security. While public interest is mostly occupied by epidemic diseases such as foot and mouth disease or avian influenza (Otte et al., 2004; Rowe et al., 2008), endemic diseases cost the United Kingdom's (UK's) livestock industry in excess of £600 million per year (Bennett and IJpelaar, 2005). This has driven a rapid increase in the exploitation of available data for animal health surveillance (AHS), which presents a significant opportunity to monitor populations and to develop new strategies for the control of endemic diseases.

This thesis focuses upon sheep scab, which is the most significant ectoparasite of sheep in the UK. Sheep scab presents a substantial welfare and economic problem to the sheep industry and historically has been very difficult to control, particularly after the deregulation of statutory control programmes in 1992 (French et al., 1999). Importantly, as the first confirmed cases of resistance to treatment were reported in 2018 (Doherty et al., 2018), the control of sheep scab is particularly timely.

1.1. Animal health surveillance

1.1.1. Introduction

Due to the ongoing coronavirus (COVID-19) pandemic, a spotlight has been shone on AHS in recent months. The expertise gathered over a number of years through the handling of novel animal diseases is being called upon to aid public health and guide the global response (Foddai et al., 2020). Whilst a wealth of information is available from the development, implementation and constant review of surveillance activities and techniques (Bisdorff et al., 2017; Department for Environment Food and Rural Affairs [DEFRA], 2011; Scottish Government, 2011 and others), AHS, which is used to detect new and emerging diseases and monitor the trends of endemic diseases, has only become a field in its own right in the past two decades (UK Surveillance Forum [UKSF], 2019). Over this time, many definitions for AHS have been proposed. In 2011, at the first International Conference for AHS, a group of experts developed a standardised definition as: “The systematic, continuous or repeated, measurement, collection, collation, analysis, interpretation and timely dissemination of animal health and welfare related data from defined populations… then used to describe health hazard occurrence and to contribute to the planning, implementation, and evaluation of risk mitigation actions” (Hoinville et al., 2013). Surveillance is therefore distinguished from monitoring as it offers feedback to stakeholders and decision-makers, allowing for the continued improvement of strategies implemented to control diseases.

1.1.2. Surveillance systems

Surveillance is delivered through the use of surveillance systems, which comprise of a number of components contributing to the "planning, implementation, and evaluation of risk-mitigating actions" (Hoinville et al., 2013). Risk-based surveillance systems generate information about a particular condition within a set population and subsequently inform the overall national surveillance strategy (OIE, 2019). The design of each surveillance system is principally dependent on the objective, or set of objectives, which assert the system's role in the wider surveillance network. Common surveillance system objectives for livestock disease include: the detection of notifiable diseases, detection of new and emerging diseases, proving freedom from diseases, and monitoring the risk and trends of endemic diseases (Middlemiss et al., 2018). However, further attributes such as the case definition, the target population, and the available resources also need to be considered in order to design an effective surveillance system (OIE, 2019). Effective surveillance systems also need to operate in a cost-effective manner.

However, irrespective of the individual surveillance system design, the fundamental components of surveillance systems are very similar. Surveillance operates through a continuous cycle of collection and collation of data, data analysis, interpretation, dissemination and evaluation (Hoinville et al., 2013).

1.1.2.1. Data collection and collation

Data collection is the foundation of all surveillance systems, as the quality and relevance of the data determines the maximum potential value of the system's outputs. Data should be representative of the population studied, minimise bias and ultimately enable the fulfilment of the surveillance system's objectives. Selecting a suitable data source therefore requires balancing specificity, data quality and representativeness of the population at risk (Barrett, 2017).

Two main frameworks exist for the collection of surveillance data: targeted ('active') and scanning ('passive'). Targeted surveillance is a scheduled risk-based approach. Due to the associated costs of this method, targeted surveillance is reserved for high-risk, notifiable, or potentially zoonotic diseases with significant economic or public health implications (Middlemiss et al., 2018). As data is purposefully collected, targeted surveillance can normally achieve a representative picture of the population at risk and minimises selection bias (Gerardo-Giorda et al., 2013). In contrast, scanning surveillance is more commonly used where the perceived economic cost is less, such as in the case of endemic diseases (Doherr and Audige, 2001). Scanning surveillance is based on the voluntary reporting of cases from a variety of sources. In Great Britain (GB) this is predominantly achieved through the Veterinary Investigation Diagnosis Analysis (VIDA) database, which is a collection of all clinical diagnoses from submissions made to the Animal and Plant Health Agency's (APHAs) veterinary investigation centres (VICs), Scotland's Rural College veterinary services (SRUC VS) disease surveillance centres (DSCs), and partner post-mortem examination providers for livestock and wildlife in GB (APHA, 2019). Scanning surveillance represents a cost-effective methodology for monitoring a variety of diseases, particularly endemic diseases, but is often subject to much higher levels of selection bias. Currently, the sources of data utilised for scanning surveillance are few; however, places such as markets, abattoirs, fallen stock centres and private laboratories are showing potential as sources of surveillance data (Barrett, 2017; Küker et al., 2018; McCue and McCoy, 2017 and others). In recognition of this, the UK's surveillance strategies are changing and encouraging the use of additional sources of data to complement and develop a more complete picture of endemic diseases (DEFRA, 2011; Scottish Government, 2011; UKSF, 2019).

While the quality of the collected data is paramount, these data must also be collated and converted into a useable format to facilitate analysis and achieve the aims of the surveillance system. For purpose-built databases, such as the VIDA database, the effort required to collate data into useable formats is often minimal, which facilitates the direct analysis of data and saves time which subsequently leads to greater outputs (Boden et al., 2017; VanderWaal et al., 2017). However, if the data were not originally intended for surveillance, they might not be formatted in an easily accessible manner. In this case, disparity between case definitions from different sources (e.g. through the use of different diagnostic methodologies) and suboptimal data management practices make interpretation and integration of these data into existing systems difficult and time-consuming (Barrett, 2017; Meidenbauer, 2017). It is estimated that, of the time spent on data processing including analysis, over 60% is taken by pre-processing time (Sun et al., 2018). As such, data which require considerable pre-processing must be sufficiently valuable to justify this expense (VanderWaal et al., 2017). Also, 'big data' are becoming more prevalent within human and veterinary healthcare fields, hence it is likely that existing methods for collection, collation, and analysis will soon be insufficient (McCue and McCoy, 2017). Another significant barrier is the lack of accessibility to potentially valuable data. Accessibility can be affected by data confidentiality requirements, ownership, formatting, and a lack of sufficient resources to best utilise these data (Gates et al., 2015; Schneeweiss, 2014). Various attempts have recently been made to try and offer a sustainable method to introduce additional complementary data for AHS purposes, such as the Rapid Analysis and Detection of Animal-related Risks (RADAR). Yet, information on the current operational status of these data sources is difficult to identify (Sala, 2016).

1.1.2.2. Data analysis, interpretation and dissemination of outcomes

Data analysis allows for the interpretation of the data in reference to the surveillance objectives and available resources. The data analysis methodologies applied are often varied in order to meet the specific objectives and fulfil the specific needs of stakeholders. Analysis methods can include: monitoring the number of cases over time, prevalence calculations, spatial distribution and modelling of disease transmission (Gamado et al., 2017; Jack et al., 2017; Rodríguez-Prieto et al., 2015).

Interpretation and dissemination of the results are the end goals of surveillance. There are a number of methods through which interpretation and dissemination are guided, which highly depend upon the surveillance objectives and the target audience (e.g. policymakers, veterinarians, farmers, etc). Current scanning surveillance outputs in the UK include quarterly disease updates on relevant endemic diseases, annual reports, and a disease dashboard which shows the number of diagnoses made for diseases in sheep, cattle, pigs and avian species (APHA, 2019b, 2020a). In general, outputs from surveillance can vary considerably. To encourage consistency in the reporting of AHS outcomes, a new set of guidelines were developed in 2019, the Animal Health Surveillance Reporting guidelines (AHSURED), which aimed to support the effective dissemination and the interpretation of AHS by the target audience (e.g. stakeholders and decision-makers) (Comin et al., 2019). The AHSURED guidelines were developed as part of the European Union's (EU) RISKSUR (risk-based animal health surveillance systems) project to deliver a comprehensive checklist of critical and optional criteria for reporting, based on the objectives of risk-based surveillance systems (Comin et al., 2019).

1.1.2.3. Evaluation of surveillance systems

The evaluation of surveillance systems, which aims to maintain effectiveness while containing costs has recently gained interest, as governments attempt to maximise the sustainability of surveillance with limited resources (DEFRA, 2011; Drewe et al., 2012; Middlemiss et al., 2018). Evaluation is not yet a routine component of most surveillance systems, and evaluations can take many forms. Most evaluations currently performed are unstructured and have been developed by the same institutions or organisations which perform the surveillance as a form of self-evaluation (Calba et al., 2015). However, two frameworks have been recently developed to allow a more standardised process of evaluation: the SERVAL (Surveillance Evaluation) framework (Drewe et al., 2015) and the RISKSUR EVA tool (Survtool) (Comin et al., 2016). Both of these methods are fairly similar in design and aim to ensure that each critical attribute is evaluated and weighted based on the objectives of the surveillance system. This ensures any conclusions made from an evaluation are not compromised from 'forgetting' critical attributes. In future, it may also be possible to employ these strategies to appraise the value of new data sources for their integration with existing surveillance (Smith et al., 2019).

1.1.3. Surveillance in practice

1.1.3.1. International examples

While the concepts of surveillance and surveillance systems are the same irrespective of geographical boundaries, countries adopt different strategies to achieve their specific surveillance objectives, dependent on risk assessment and available resources. Across the EU in particular, AHS is regarded as an essential activity to maintain public health, animal health, and international trade relationships. Therefore, AHS is often publicly funded and operated (Häsler et al., 2014). However, this is not the case in Denmark, where AHS became privately operated in 2008 as the cost of public surveillance centres outweighed their benefit due to the low risk of introducing disease (Scottish Government, 2011). Conversely, the risk of introducing new or emerging diseases is much higher in countries, such as the United States of America (USA), where international trade is a significant component of agriculture (Mourkas et al., 2020), with surveillance needing also to be representative of a much larger area. Consequently, the approach to AHS in the USA is managed by different public agencies dependent on the disease, with the surveillance of notifiable diseases being managed at a federal (national) level, and non-notifiable at a state-level (United States Department of Agriculture, 2020).

1.1.3.2. Approach to AHS in GB

In GB, AHS is publicly subsidised and operated. As previously described in 1.1.2.1, the majority of scanning surveillance is conducted through the network of VICs and DSCs operated by the APHA and SRUC VS respectively. Diagnoses reached at these centres from diagnostic samples and necropsies contribute to the VIDA database, which is used to detect new and emerging threats and monitor endemic diseases. However, AHS in GB has been under increasing scrutiny over the last decade. In 2011, two key reports for the future of AHS in the UK were published. One was released by the DEFRA to evaluate the 2003 Veterinary Surveillance Strategy (VSS), and the other by the Scottish Government, also known as the 'Kinnaird' report, which offered the first independent review of AHS in Scotland. The recommendations made in both reports resulted in the restructuring through closure of government-operated or subsidised laboratories, and the formation of more centralised hubs for diagnostics aiming to provide more cost-effective surveillance without impinging on the representativeness, sensitivity and quality of its outputs (DEFRA, 2011; Scottish Government, 2011). The proposal of centre closures created much concern from industry, veterinarians and farmers (*Veterinary Record,* 2014; House of Commons Welsh Affairs Committee, 2012). Irrespective of public concerns about the loss of local centres, seven VICs in England and Wales were closed in 2013 and 2014, and three new third-party post-mortem providers (based at universities) were created. Similarly, as part of the new surveillance strategy in Scotland, restructuring of services has also taken place more recently. This has resulted in three DSCs centres becoming "Veterinary Surveillance Hubs", the inclusion of a third-party post-mortem provider (University of Glasgow) and all of the remaining DSCs providing only post-mortem services, with centralization of all the testing in Edinburgh (SRUC, 2019).

Additionally, both the Kinnaird report and a more recent UK-wide surveillance strategy report in 2018, concluded that there is still considerable scope to provide surveillance more efficiently. Focus is now shifting to include available information from other existing data sources (e.g. private labs, health schemes and abattoirs), with an emphasis on collaboration to develop a more representative picture of animal health, particularly for endemic diseases (Middlemiss et al., 2018; Scottish Government, 2011). However, access to such data for surveillance has been historically challenging, mainly due to privacy concerns, lack of standardisation (Drewe et al., 2014), and the associated labour requirements to produce outputs from this data. Furthermore, despite considerable efforts to create a robust surveillance network, it is likely that AHS in the UK will undergo further significant changes with Brexit, as many policies adopted EU guidelines. In addition, much funding for agriculture currently emanates from EU funds, such as the EU Common Agricultural Policy (European Commission, 2020). A scenario planning workshop conducted in 2017 which considered 5 potential situations post-Brexit, highlighted the need to create a more resilient surveillance network amongst such uncertainty (Boden et al., 2017). Based on these future considerations, the importance of AHS against the current constraints has highlighted the importance of critically evaluating our existing systems, of becoming more proactive in identifying new data sources and in developing more sustainable and cost-effective solutions to AHS in GB.

1.2. Sheep scab

1.2.1. Introduction

Sheep scab, caused by the non-burrowing *Psoroptes ovis* mite (Kirkwood, 1986), is one of the oldest yet most important ectoparasitic disease of sheep (Cato and Dalby, 1998; Nieuwhof and Bishop, 2005). The *P.ovis* mite is an obligate parasite which abrades the skin of the sheep. Antigens produced by the mite initiate the host's hypersensitivity response and simulate the release of serous exudate at the site of the abrasion. The mites feed on the exudate, reproduce, and continue in a feedback loop of abrasion and exudate production which causes skin lesions to form across the body of the sheep (Figure 1.1). Sheep scab typically has a long subclinical phase which can last several weeks even in naïve animals (Bates, 2009; van den Broek and Huntley, 2003). The complete lifecycle of the *P.ovis* mite takes between 11-19 days dependent on conditions (van den Broek and Huntley, 2003): adult females can live between 11-42 days, depositing 1-6 eggs per day for up to 29 days, and thus after the first 10 days following infestation the number of mites doubles every 6.3 days (van den Broek and Huntley, 2003). In the clinical phase of infestation, sheep become extremely pruritic and engage in self-mutilating behaviour (Berriatua et al., 2001; Corke and Broom, 1999), with prolonged infestations causing hypoproteinaemia from albumin loss, resulting in ill-thrift and emaciation (Sargison and Busin, 2014).

Figure 1.1: *Sheep with a severe case of sheep scab, with wool loss and extensive lesions. (Photograph: Dr. Valentina Busin)*

1.2.2. Epidemiology

1.2.2.1. Transmission

Sheep scab is transmitted through both direct and indirect contact. Direct contact transmission occurs at close proximities, when an infected sheep comes into contact with a naïve sheep (Berriatua et al., 1999). As such, housing sheep over winter or during lambing and during management activities can particularly expedite the natural transmission dynamics (Kirkwood, 1986). Despite being an obligate parasite, the *P.ovis* mite can survive for almost four weeks off the host and be infective for up to two weeks, dependent on the ambient temperature and humidity (van den Broek and Huntley, 2003). Therefore, transmission can also occur from the environment, such as from fence posts or handling facilities (Berriatua et al., 1999). For this reason, treated sheep should not be reintroduced onto infected land, where transmission will occur again, which might prove very difficult for some farming systems. Consequently, sheep scab control becomes particularly difficult in some areas, especially for holdings which rely on common grazing (Rose et al., 2009).

1.2.2.2. Prevalence

In 1992, the last year of the mandatory dipping programme, less than 100 sheep scab cases were recorded (French et al., 1999). However, over the following years, the number of cases spiked, exceeding 7,000 outbreaks in 2004 (Bisdorff et al., 2006). As a result, sheep scab is now considered endemic in GB (Sargison et al., 2007). At present, the national prevalence of sheep scab in GB is estimated to be around 9% (Bisdorff et al., 2006; Rose et al., 2009), however significant regional variation has been shown. From a number of surveys and interviews, Wales has been estimated to have the highest prevalence of sheep scab in GB, between 16% and 36% (Chivers et al., 2018; Cross et al., 2010; Rose et al., 2009). Other areas with a high prevalence of sheep scab infestations include the north of England, south west England and Scotland (French et al., 1999). The significant variation in prevalence per region highlights the importance of obtaining an accurate picture of the distribution of sheep scab in a particular area, also called "hotspot", as well as its change over time. Interestingly, 85% of the farms that reported a sheep scab outbreak, as part of a survey conducted by Rose & Wall (2012) during 2007/2008, had already experienced a previous outbreak, suggesting that flocks might not be managing to fully control the disease on their premises, leading to repeated outbreaks. On the contrary, almost 80% of farms in Wales which did not have a sheep scab outbreak, had not experienced one in the last 10 years either (Chivers et al., 2018).

In addition to exhibiting a strong regional variation in prevalence, sheep scab is widely considered a seasonal disease, with the majority of infestations occurring in the winter months. This seasonality is thought to be influenced by the climate, with improved off-host survival in the lower temperatures of winter than in summer (Smith et al., 1999). For their continued survival in suboptimal circumstances, it has been suggested mites seek "cryptic sites" such as skin folds and the ear canals where they remain asymptomatic over summer (Nisbet, 2011). However, this seasonality might also be related to a number of management practices, like the traditional summer shearing to reduce the fleece length (French et al., 1999). Hill sheep are traditionally gathered and handled in the summer months for prophylactic application of acaricides and anthelmintics, and the mandatory dipping also occurs in the summer months, the residual effect of which would suppress infestations for up to two months (French et al., 1999).

1.2.3. Diagnosis & treatment

1.2.3.1. Diagnosis

The diagnosis of sheep scab is commonly confirmed through a skin scraping. This involves taking skin samples for microscopic examination from lesion sites using a scalpel blade. Until recently, skin scrapings were the only diagnostic option. However, in 2017, a new sheep scab enzyme-linked immunosorbent assay (ELISA) for the detection of antibodies to the sheep scab-specific allergen *Pso o 2* using blood samples was commercialised (Burgess et al., 2012; Nunn et al., 2011). The sheep scab ELISA, developed at Moredun Research Institute (MRI), offers a test with a high sensitivity and specificity – 98.2% and 96.5% respectively (Hamer et al., 2019) – which can diagnose subclinical disease as early as 2 weeks after infestation, before clinical signs develop (Burgess et al., 2012). Furthermore, the sheep scab ELISA is designed to monitor presence of the parasite at a flock level, which could be particularly instrumental for decreasing reliance on the prophylactic use of acaricidal products, a priority since the first case of resistance to one of the commonly used products has been reported (Doherty et al., 2018).

1.2.3.2. Treatment

There are only two licensed products for the treatment of sheep scab: organophosphate (OP) plunge dips and injectable macrocyclic lactones (MLs). OPs are very effectual, but their main limitations are the structural infrastructure required and the health risks to the operators (Blain, 2001). Dip removal and disposal can also prove problematic and as a consequence OPs have fallen out of use in favour to the more convenient injectable MLs. In a recent survey, over 95% of farmers relied on MLs to treat clinical sheep scab outbreaks, with only 15% using OP dips (Chivers et al., 2018). MLs offer a more convenient solution for the control of sheep scab as they can be administered to sheep of all ages and do not require a dedicated infrastructure for delivery. They are also effective against nematodes which increases their attractiveness to use, but this also increases the selection pressure by increasing their repeated use over time.

Unfortunately, with limited treatment options for sheep scab and the widespread use of MLs, it is not surprising that the first case of resistance to MLs was confirmed in 2018 (Doherty et al., 2018; Sturgess-Osborne et al., 2019). This raises much uncertainty about the future treatment options for sheep scab, especially if reliance on MLs cannot be reduced. Resistance to the MLs will shift pressure onto the OPs, for which resistance would likely develop too after the withdrawal of other treatment products (such as the synthetic pyrethroids) from the market.

1.2.4. Economic impact

In 2005, it was estimated that sheep scab costs the sheep industry approximately £8.3 million per year (Nieuwhof and Bishop, 2005), with £0.8 million due to productivity losses and the remainder from treatment costs. This estimate is now regarded as low, not accounting for labour costs, the cost of the subclinical phase, or ineffective treatments (including antiparasitic resistance) (Nixon et al., 2017). In addition to the direct cost of treatment, infected animals have also been shown to experience a decreased lambing percentage, low lamb birthweight, increase in lamb mortality, and increase in barren rate (Nunn et al., 2011; Scott et al., 2007). More recent estimates show that sheep scab costs £40.84 per ewe in lowland flocks, and £35.12 in upland flocks (Nixon et al., 2017). These figures represent a substantial proportion of the sheep's economic value, which would significantly reduce any margin for profit (Harvey and Scott, 2020). Indirectly, sheep scab also affects other industries such as the wool and leather. As a results of sheep scab, unusable sheep pelts are estimated to cost the leather industry in excess of £15 million per year (Coles, 1998).

1.2.5. Control of sheep scab

1.2.5.1. International examples

Sheep scab has been reported in 149 countries (Kirkwood, 1986); however, successful eradication has also been achieved on a number of occasions with different methods. In New Zealand, sheep scab was successfully eradicated in 1985 (ADAS, 2008). This was led by the public sector, with eradication achieved through targeted surveillance and legislation introduced in 1849 (Davidson, 2002). At this time, toxic but effective dips containing arsenic, very different to today's compounds, were used for compulsory dipping, which steadily decreased the prevalence. When the disease was brought to manageable levels, the localised disease clusters were tackled through slaughter of affected flocks and stray sheep (Davidson, 2002). Similar techniques for eradication were also applied in Australia, where sheep scab was eliminated in 1984, a year before New Zealand (Animal Health and Welfare Wales, 2018). Notably, eradication has also been achieved in the USA and Canada, in 1973 and 1924 respectively (ADAS, 2008). In countries where eradication has been successful, reintroduction is always a significant risk. To prevent this, strict biosecurity protocols must be followed, complemented by an effective and timely surveillance system to quickly identify and prevent the spread of outbreaks. Unfortunately, in many countries, like Sweden, Norway and Denmark, eradication was achieved across the late 19th to mid-20th centuries only to be reintroduced in the 1970s (Kirkwood, 1986).

1.2.5.2. Past control measures in Great Britain

Sheep scab has been a well-known presence in GB for centuries, and numerous attempts at control have been made over the years. The first legislation for sheep scab in GB dates back to as early as 949AD, when King Hywel Dda of Wales banned the sale of 'scabby' sheep in the winter months and keeping sheep on land where scabby sheep had resided in the past 7 years (ADAS, 2008).

The first period of notifiable status in GB was introduced in 1869 (Watson, 1976), but did not mandate the treatment or isolation of infected animals and was not sufficient for control.

At the time, many sheep were also being imported to GB from Ireland and the Americas, which only compounded the problem (Page, 1969). Then, the introduction of the Sheep Scab Order (1898) meant veterinarians were required to diagnose the reported cases of sheep scab, and thus the number of cases per year dropped from 2,514 to 1,379. But it was not until the Sheep Scab Orders of 1903, 1905 and 1907, that the treatment of sheep scab was made compulsory, through a regulated (sheep had to be dipped for 30 seconds) and compulsory annual dipping programme (Page, 1969). These treatments, however, were not fully effective, so double-dipping (two weeks apart) was introduced in 1914. This was significantly more effective, and the number of cases reduced drastically to 226 per year. After some variation in the number of outbreaks seen during the First World War, the dipping interval was increased from 30 to 60 seconds, to reach mites that resided in cryptic sites (Kirkwood, 1986). Despite these efforts, sheep scab was still seemingly impossible to eradicate. However, in 1948 the introduction of new formulation with a longer residual effect, the organochlorines, made a single dip for a minimum of 60 seconds more effective, and elimination in GB was achieved in 1952 (Kirkwood, 1986).

Mandatory dipping was phased out after elimination, and the country remained free from sheep scab for 21 years. However, unfortunately, in 1973 sheep scab was reintroduced. It was first identified on a farm in Lancashire and thought to have been reintroduced from animal imports from Ireland (Kirkwood, 1986). Localised dipping programmes were introduced to control its spread, but these were unsuccessful and led to the reintroduction of a national mandatory autumn double-dip in 1976 (Kirkwood, 1986; van den Broek and Huntley, 2003), which was implemented under the Sheep Scab Order (1977) (Henderson, 1990).

Mandatory dipping continued across different formats, with summer dipping also being introduced nationally in 1982 (Kirkwood, 1985). The number of cases per year during this time fluctuated but largely remained around 100 per year. The lowest number of outbreaks was 36 in 1988, but subsequently increased (ADAS, 2008). Sheep scab was ultimately deregulated in 1992 as eradication was deemed unfeasible and expensive (ADAS, 2008). As such cases spiked significantly from less than 100 per year prior to 1992, to an estimated 7,000 by 2003 (Bisdorff et al., 2006).

In contrast to the rest of GB, the Shetland Isles are free from sheep scab. A small-scale outbreak was identified in 1993, but all sheep within 10 miles were then dipped to successfully prevent its spread. All sheep are now injected with Dectomax, a ML, as part of the quarantine procedures when imported to the Isles (Harmsworth, 1997). Shetland also has its own legislation in place, the Sheep Scab (Shetland Isles) Order 2003. This allows the council to inspect and test for sheep scab mites upon import, and a minimum of a 48-hour quarantine period for imported animals (Scottish Government, 2003).

1.2.5.3. Current control measures in GB

The legislation currently in place in England and Wales is the Sheep Scab Order (1997), which mandates the treatment and bans the movement of visibly affected sheep (Minister of Agriculture, Fisheries and Food, 1997). By contrast, in Scotland (with the exception of the Shetland Isles) sheep scab was reinstated as a notifiable disease in 2010 through the Sheep Scab (Scotland) Order (2010) (The Scottish Government, 2010). However, despite these current legislative measures, sheep scab remains a significant welfare and economic problem to the industry. Historically, many control efforts were effective, but under the current circumstances and its endemic status, achieving control of sheep scab in GB is likely to be challenging. Therefore, the development of future control measures needs to exploit all sources of data to provide solid and evidence-based basis towards a cost-efficient and effective path to control.

1.3. Aims

Using sheep scab as a model, this research project aims to enhance the use of existing surveillance data and evaluate new data sources to guide future control strategies for sheep scab. This will be achieved through the collection, collation and analysis of two data sources: the existing scanning surveillance VIDA database, and the data from the sheep scab ELISA. More specifically, this project has the following objectives:

- To use the existing scanning surveillance data to identify current trends and geographical "hotspots" for the target of future control measures (Chapter 2).

- To use the existing scanning surveillance data to investigate the impact of national targeted disease control initiatives and inform on their use as part of future control measures (Chapter 2).

- To provide a new usable source of data through digitisation of all data from the sheep scab ELISA (Chapter 3).

- To provide information on the current use and uptake of the sheep scab ELISA and evaluate the risk associated with certain management practices (Chapter 3).

- To investigate the potential value of the sheep scab ELISA data as a complementary source of scanning surveillance (Chapter 3).

This research also represents the first work package of a larger multidisciplinary project: Department for Environment, Food and Rural Affairs (DEFRA) – Veterinary Medicines Directorate (VMD) Lot 2 Antiparasitic Resistance: Sheep Scab, which will provide the foundation for further analysis and modelling of a range of disease control scenarios, for the ultimate goal to identify the optimum pathway towards better targeted and coordinated activities across the sheep industry.

2. Exploiting the use of existing scanning surveillance data for sheep scab

2.1. Introduction

The development of sustainable and cost-effective strategies is paramount to facilitate the control of endemic disease. Currently, surveillance of endemic diseases in GB, including sheep scab, is predominantly achieved through the VIDA database (as described in 1.1.2.1). However, the possibility of further exploiting the use of this data is increasingly recognised, hence the government is promoting sharing of this data to increase output and encourage a more cost-effective approach to the control of endemic diseases (Middlemiss et al., 2018).

In the case of sheep scab, the first steps towards developing effective control strategies is to improve the understanding of its spatial and temporal trends. As sheep scab has previously shown a high regional variation in prevalence (French et al., 1999; Rose et al., 2009), areas with a high disease burden also need to be identified to focus efforts for disease control. An important concept for monitoring the true prevalence of a disease also includes knowing the proportion of disease within the population at risk. However, with diagnostic datasets such as the VIDA database, an appropriate denominator for this data is often not available, which can be a limitation for its interpretation (Tongue et al., 2020).

There are often many approaches tried in an attempt to control endemic diseases due to their complexity. For sheep scab, since the removal of the statutory control programme in 1992 (French et al., 1999), a number of targeted disease control initiatives have been adopted to improve the awareness and knowledge of the disease and contribute towards control. These initiatives are normally industry or government funded, run for a limited period of time, and are working towards a set goal such as increasing awareness, providing education about the disease, and advice on treatment options (Department of Agriculture Food and the Marine, 2017). Yet, such initiatives are often expensive, time consuming and difficult to coordinate. Therefore, the impact of these initiatives requires to be evaluated, which could provide guidance to their effectiveness as a tool for sustainable and cost-effective control.

To aid in the evaluation of impact and guide future initiatives, temporal aberration detection algorithms (TADAs) could be utilised. TADAs are conventionally used as bio-surveillance tools to detect outbreaks of pathogens in hospital settings (Yuan et al., 2019). The application of a TADA can identify a statistically significant increase in the number of cases over time, from a predetermined background level of disease. When a statistically significant increase occurs, an alarm is raised which indicates a potential outbreak (Höhle and Mazick, 2010; Salmon et al., 2016; Zhou et al., 2015). These systems can offer a real-time evaluation of disease, which makes them a very important tool within public health. However, increasingly, their application for other purposes is also being acknowledged, particularly within veterinary medicine (Tongue et al., 2020).

This chapter, therefore, aims to use the VIDA database to identify current trends and geographical "hotspots" for sheep scab. Furthermore, it aims to explore the potential utility of the TADAs to retrospectively investigate the impact of previous national targeted disease control initiatives and inform on their use as part of future control measures.

2.2. Material and methods

2.2.1. Data collection and description

2.2.1.1. VIDA data collection

As described in 1.1.2.1, the VIDA database records all diagnostic submissions made to the APHA's VICs, SRUC VS DSCs, and partner post-mortem providers where a final diagnosis has been reached by one of the Veterinary Investigation Officers (VIO) working in the centre. Samples are routinely submitted on a voluntary basis from referring private veterinarians and farmers for diagnostic investigations. The submissions can include one or multiple samples and the sample material can range from blood, milk, tissue or faecal samples to whole carcasses. When a diagnosis (or multiple diagnoses) is reached, it is assigned one (or multiple) VIDA codes by a VIO. VIDA codes are given to submissions where the diagnosis meets pre-determined and defined criteria.

For the diagnosis of sheep scab, the VIDA database includes only diagnoses made at the APHA and SRUC VS laboratories through a standardised and United Kingdom Accreditation Service (UKAS) accredited skin scrape test, to directly identify the *Psoroptes ovis* mites from skin scrape samples through microscopy. Skin scrape samples are taken using a scalpel blade on the outside edge of a lesion site by a private veterinarian. At the laboratory, skin scrapes are examined under low power microscopy (X100) by the veterinary investigation officer (VIO) to determine the presence of mites. If no mites are detected from the initial microscopy a digest is performed. The digest involves boiling the sample in a potassium hydroxide solution to dissolve any hair and lesion material in the sample, to allow for easier visualisation of mites that may have been trapped in lesion crusts. Once the digest has been performed the sample is again examined by low power microscopy (Ministry of Agriculture Fisheries and Food, 1971). If a positive sheep scab diagnosis is reached for at least one sample within a submission, the submission is assigned the VIDA code '390'.

For the purposes of this study all submissions that were assigned the code '390' (herein referred to as 'positive scrapes') were extracted from the VIDA database, together with their submission date and a regional geolocator, from January 1995 to September 2019 inclusive. However, due to incompleteness of the data in early years, the foot-and-mouth disease epidemic in 2001, and the subsequent restocking of livestock in 2002 as a result of the outbreak, only data from January 2003 onwards were included in the analysis.

2.2.1.2. Denominator data

To determine an appropriate denominator for the analysis of positive scrapes, four potential datasets were also obtained from the VIDA database. The individual descriptions of each datasets are listed in Table 2.1. All datasets were extracted as a total count per year for the 16-year study period (2003 to 2018).

Table 2.1: *Description of the datasets available as potential denominators extracted from the VIDA database*

Name of dataset	**Description**
Total diagnostic submissions	Count of all diagnostic ovine submissions submitted to the APHA, SRUC VS and partner post-mortem providers. Samples could contain any type of sample material (e.g. carcass, blood, faeces etc.) from an ovine. Where multiple samples (of any type) were included within one submission, this was regarded as a single submission.
Skin submissions	Count of all diagnostic ovine submissions where the main presenting sign on the submission form was recorded as “skin” by the submitting private veterinarian.
Scheduled scrapes	Count of the number of scheduled (made by the VIO) skin scrape tests for ovines. The tests included: the APHA's test code 'TC81' for an ectoparasite examination and the SRUC test codes "MicrSk" for microscopic examination of the skin or hair, "Shscab" for sheep scab examination, and "Skpara" for microscopic examination for lice or mites. Where multiple skin scrapes were scheduled for one submission, this was recorded as 1 scheduled scrape.
Scrape submissions	Count of all skin scraping submissions (made by the private veterinarian) of ovines.

2.2.1.3. Sheep scab initiatives

To identify all the targeted sheep scab disease control initiatives which took place during the study period across GB and collect details of each, a variety of sources were consulted. Primarily, information regarding the initiatives derived from publicly available sources such as peer-reviewed literature, government and industry reports. Besides this, industry and government experts were also consulted to capture initiatives where there was no, or insufficient, information otherwise available. National initiatives, i.e. those which took place in one or more of the three countries in GB, were selected as they were designed to reach a larger portion of the population at risk, featured well-defined start and end dates, and had a higher proportion of information available from primary sources. All the initiatives identified and collated across all countries were categorised into a 'type' which pertained to the planned actions of the initiative to allow grouping of initiatives. These categories were:

'free testing', where the cost of skin scraping tests was waived or subsidised; 'knowledge transfer & skills training', where education was provided through workshops and training sessions; 'knowledge transfer & free testing', where education was provided, coupled with free skin scraping tests; and 'legislation', where a new legislation was introduced beyond the scope of the current Sheep Scab Order (1997).

2.2.2. Data analysis

All data analyses and visualisations, unless otherwise stated, were performed in R version 3.5.1 and RStudio.

2.2.2.1. Spatial analysis

The data from positive scrapes were provided with a regional geolocator, approximate to county-level, which was used to descriptively assess the spatial distribution of sheep scab across GB during the study period. The counts were aggregated by region, (i) firstly per year for the full study period and then (ii) totalled across all years. The aggregated totals were mapped using a shapefile provided by the APHA, including the correct boundaries of the regions defined in the dataset. In addition, the location of the DSCs and VICs were determined and plotted by extracting longitude and latitude from their postal codes using the Office for National Statistics' (ONSs) Postcode Lookup database (Office for National Statistics, 2019a).

2.2.2.2. Temporal analysis

The total number of positive scrapes were plotted by year to assess the temporal pattern of sheep scab across GB during the study period. A Poisson regression was then applied to test the effect of year on the number of positive scrapes. The combination of this analysis with the provided regional geolocator was used to plot the positive scrapes by year and country to assess the temporal difference among England, Scotland and Wales. Subsequently, a Pearson's Chi-squared test was performed to ascertain whether the difference was significant. The count of positive scrapes was also grouped by month across the whole study period to investigate the seasonal pattern of sheep scab.

2.2.2.3. Denominator analysis

The total counts of the four datasets were directly compared to the number of positive scrapes for the 16-year study period (2003 to 2018). Then, the selected potential denominators were visualised as counts per year compared to the number of positive scrapes, to provide a percentage and act as denominator(s) for the interpretation of the VIDA positive scrapes.

2.2.3. Aberration detection

A temporal aberration detection algorithm (TADA) was applied retrospectively to measure the impact of disease control initiatives on the number of positive scrapes recorded in the VIDA database. The original Farrington algorithm, which uses an over-dispersed quasi-Poisson regression-based method for weekly aberration detection, was applied to this dataset due to its suitability for count data, ability to account for seasonality, and good sensitivity using the 'surveillance' package in R (Farrington et al., 1996; Höhle and Mazick, 2010; Zhou et al., 2015). To use the TADA, firstly a period free from suspected aberrations (i.e. a baseline period) is required to train the model. The quality and length of this baseline period is crucial, determining the sensitivity of the model (i.e. its ability to detect true aberrations) using a defined significance level (set at $\alpha = 0.01$). When the TADA is applied to the entire dataset, excluding the baseline ('training') period, an alarm is generated if the observed number of counts (i.e. positive scrapes) exceeds the upper threshold predicted by the algorithm, denoting a significant aberration.

As the sheep scab initiatives were specific to each country within GB, a separate TADA was performed for each country. The Farrington algorithm utilised the number of positive scrapes per country, aggregated by week in accordance with the ISO 8601 international standard of time and date (International Organization for Standardization, 2004). The weekly aggregates were then subsequently visualised as a time series to evaluate the most appropriate baseline period, ensuring there were no suspected aberrations or disease control initiatives before the TADA was applied.

2.3. Results

2.3.1. VIDA descriptive analysis

A total of 2,401 positive scrapes were recorded between the 1st January 2003 and 31st December 2018. As displayed in Figure 2.1, a significant decrease was observed in the annual count of positive scrapes from the beginning of the study period ($p < 0.001$). The maximum recorded number of positive scrapes was in 2004 (n = 277), falling to the lowest in 2015 (n = 55). In contrast to the overall decline observed over the study period, the number of positive scrapes increased by over 2.5 times from 2017 (n = 68) to 2018 (n = 172).

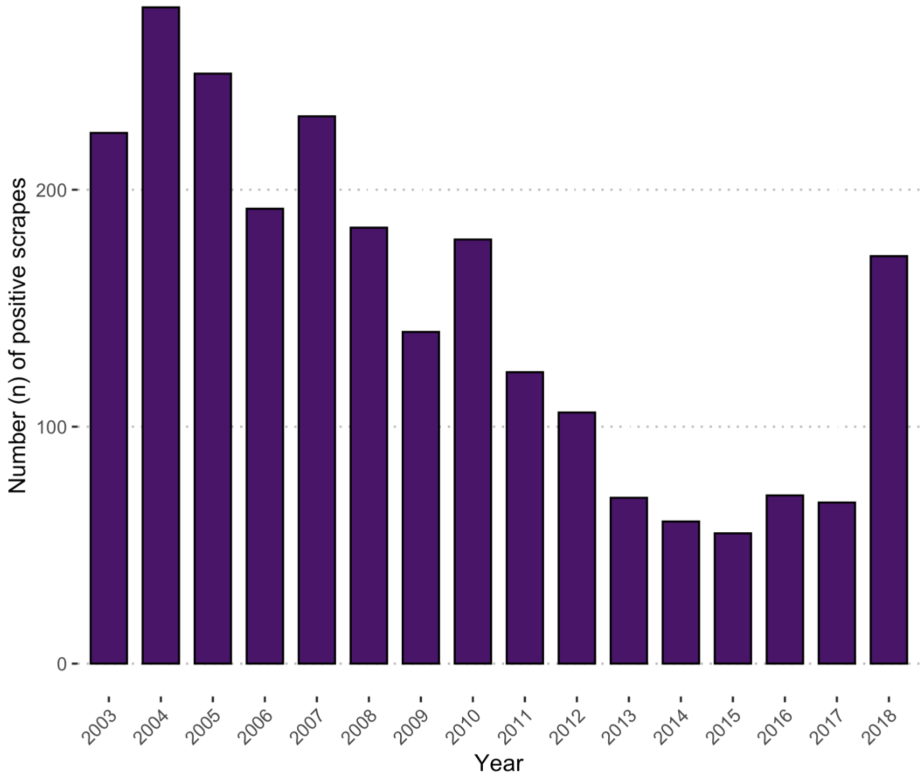


Figure 2.1: *Annual trend of positive scrapes (n = 2,401) from 2003 to 2018.*

Of the total count of positive scrapes, 2,310 included a geolocator from which the country information could be derived. The annual pattern of positive scrapes per country is displayed in Figure 2.2. Overall England, Wales and Scotland presented a similar pattern, with a prolonged but fluctuating decline over the study period, with the exemption of a sharp increase in counts in Wales in 2018. Wales exhibited consistently higher counts of positive scrapes compared to England and Scotland, with the highest count in 2004 (n = 134). The only year where the number of positive scrapes was higher in Scotland (n = 29) than in Wales (n = 19) was in 2014. In England, the highest count of positive scrapes was also observed in 2004 (n = 84), and after a consistent decline, the lowest count occurred in 2015 (n = 9). In Scotland, highest number of positive scrapes was in 2003 (n = 60), and the lowest in 2017 (n = 17). Finally, a statistically significant difference was shown between the total number of positive scrapes of the three countries (p < 0.001).

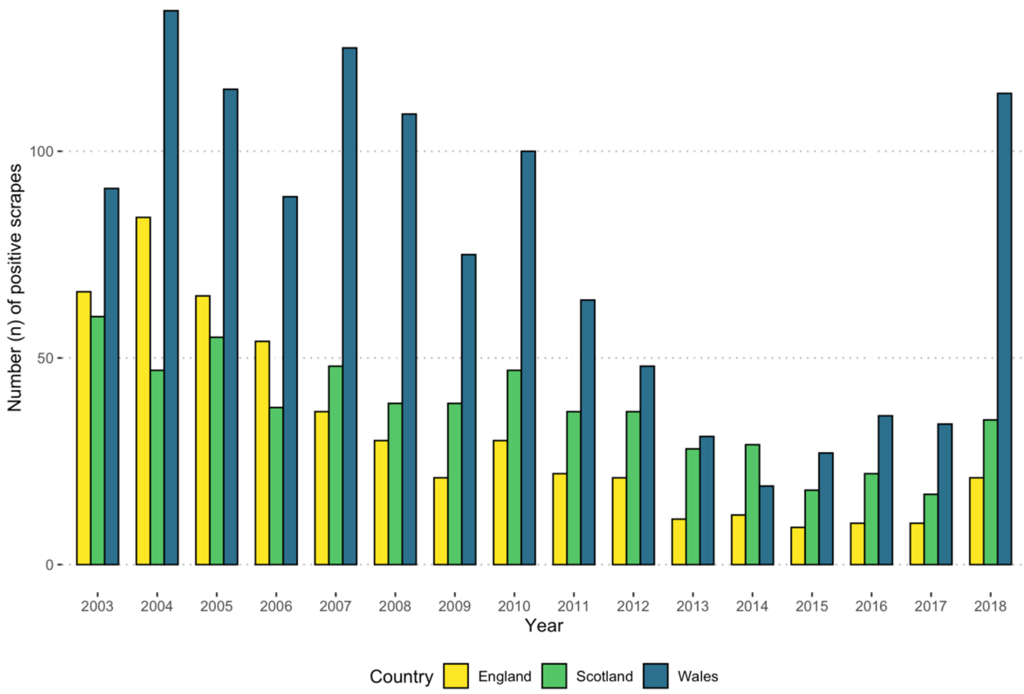


Figure 2.2: *Annual trend of positive scrapes per country (n=2,310) from 2003 to 2018.*

The overall distribution of positive scrapes by month shown in Figure 2.3 displays a strong seasonal pattern. The highest number of positive scrapes occurred in January (n = 475). Higher counts were observed across autumn and winter, specifically between October and March (mean = 300 positive scrapes per month). Lower counts numbers were observed in the summer months from April to September (mean = 100 positive scrapes per month), with the lowest occurring in June (n = 62). This seasonal pattern of positive scrapes was also similar between the three countries, with the exception of England in September which displayed the lowest number of positive scrapes in a single month (n = 12) (Appendix 1). Furthermore, for two months, May 2013 and July 2018, no positive scrapes were reported (Appendix 2).

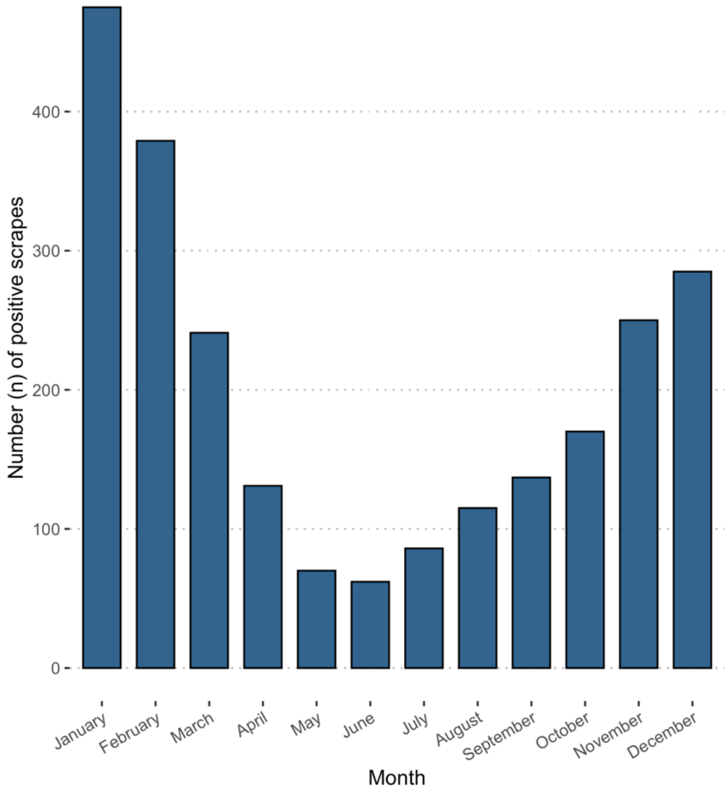


Figure 2.3: *Monthly aggregate of positive scrapes (n = 2,401) from 2003-2018.*

2.3.2. Denominator selection

Of the four datasets analysed, 'total diagnostic submissions' had the highest count (n = 146,199), and (as shown in Table 2.2) the total number of positive scrapes (n = 2,401) represented, therefore, a very small proportion of this potential denominator. As a result, 'total diagnostic submissions' was excluded from consideration as a potential denominator.

Table 2.2*: The total count of submissions included for each dataset, and the percentage of the total number of positive scrapes (n = 2,401) for the study period (2003-2018).*

Dataset	Total count	Total positive scrapes as a percentage of the total denominator count (%)

Total diagnostic submissions	146,199	1.6%
Skin submissions	8,146	29.5%
Scheduled scrapes	5,171	46.4%
Scrape submissions	1,932	124.3%

The datasets 'skin submissions', 'scheduled scrapes' and 'scrape submissions' all displayed similar annual trends (Figure 2.4). Despite having a similar trend to the count of positive scrapes, the number of 'scrape submissions' was consistently below that of the positive scrapes, and consequently the total number of positive scrapes represented 124.3% of these submissions (Table 2.2).This implies that many cases of sheep scab were diagnosed from submissions other than skin scrapings (e.g. carcasses). Based on this, 'scrape submissions' was also excluded as a potential denominator, as it did not account for sheep scab diagnoses made from other sample types.

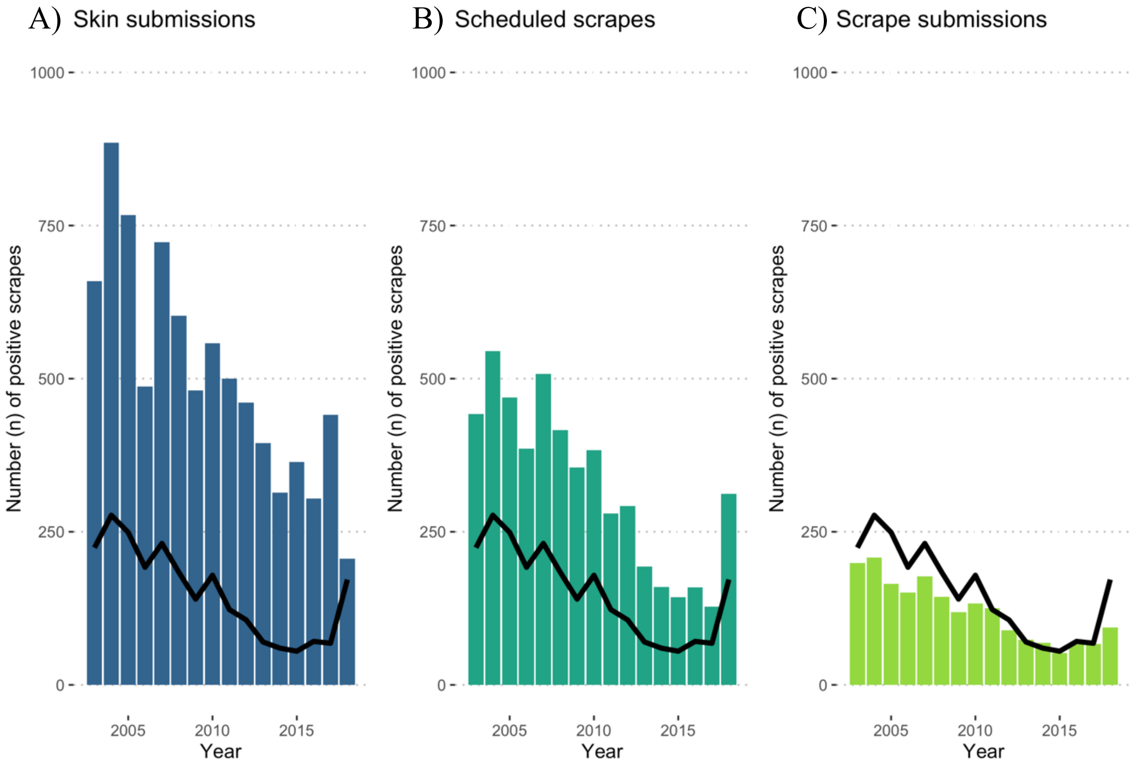


Figure 2.4: *Annual trend of three potential denominators, overlaid by the yearly totals of positive scrapes (black line). A) Skin submissions (n = 8,148). B) Scheduled scrapes (n = 5,171). C) Scrape submissions (n = 1,932).*

2.3.3. Descriptive spatial analysis

In total, 2,310 of the 2,401 positive scrapes (96.2%) included a regional geolocator which allowed them to be categorised into 69 defined geographical regions across GB (7 in Wales, 14 in Scotland, and 48 in England). At the beginning of the study period, 25 VICs were in operation across GB. As of the end of 2018, 18 of these were still operational. All closures during the study period took place in England, with one closure in 2013, and the other 6 in 2014 (Figure 2.5).

Figure 2.5 displays the total counts across the full study period (2003-2018), overlaid by the VIC locations which have been in operation since the start of the study period, and their operational status at the end of the study period in 2018. The number of cases across GB was unevenly distributed across the study period, with 52.4% of cases originating from Wales, 25.8% from Scotland and 21.8% from England. The county with the highest number of positive scrapes across all years was Ceredigion, representing 16.4% of the total diagnoses (Table 2.3). Ceredigion also represented the focal point within Wales, with the adjacent North West Wales, Powys and Carmarthenshire also displaying high counts as seen in Table 2.3. Of the 7 Welsh regions, 5 were within the 10 regions with the highest total positive scrapes, with the other 5 regions all within Scotland (Table 2.3). In England, the region with the most positive scrapes was Devon with 52. Regions with 0 positive scrapes within the study period were Berkshire, Cambridgeshire, East Riding & North Lincolnshire, Hertfordshire, Merseyside, Tyne & Wear, Eileanan an Iar and Shetland.

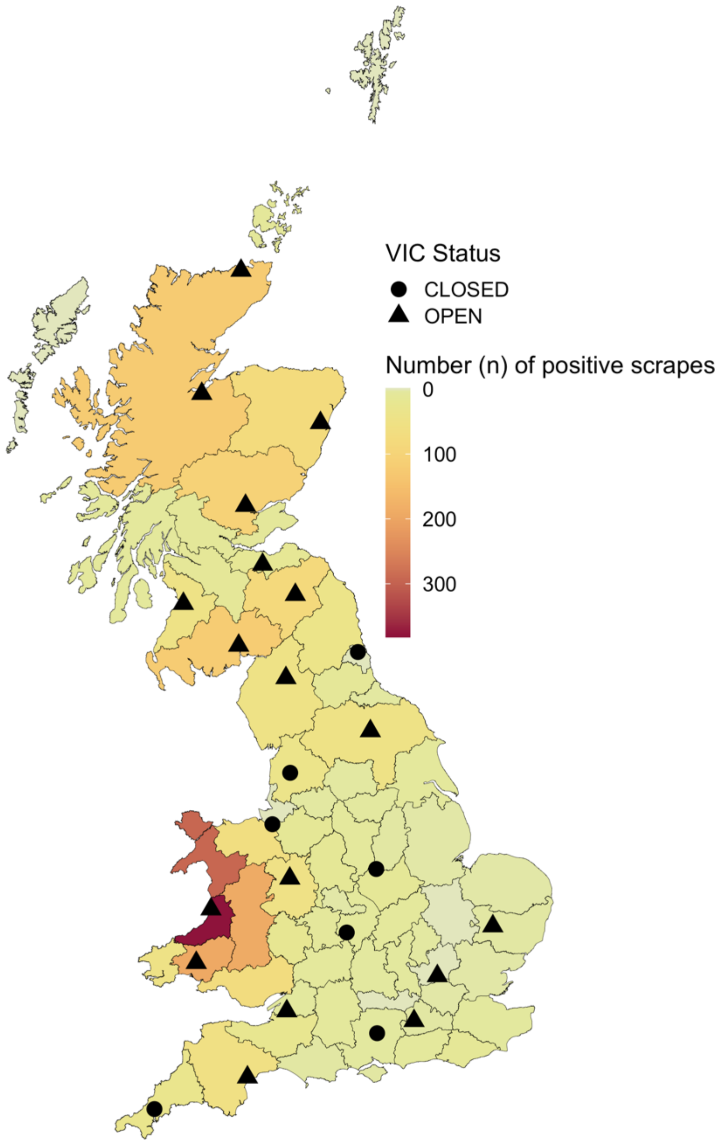


Figure 2.5: *Spatial distribution of the total VIDA positive sheep scab submissions from 2003-2018. Points overlaying this represent the disease surveillance centres and veterinary investigation centres which have been open during the study period. The shape of the point, a circle or triangle, represents the centre's current status: closed or open respectively.*

From the study period, 4 years (2003, 2007, 2013 and 2018) were selected to represent the changes in the spatial distribution of the count of positive scrapes (Figure 2.6). The count of positive scrapes in 2003 (Figure 2.6 A) saw a maximum of 26 positive scrapes in one region, North West Wales. Overall, the highest number of positive scrapes was seen across the west of Wales, which included Ceredigion, Carmarthenshire and North West Wales (n = 20-26) and in Tayside, Scotland (n = 11). In 2007 (Figure 2.6 B), Ceredigion observed the highest number of positive scrapes seen in one county across all years, with a total of 47. This peak in Ceredigion also aligned with a more generalised increase in positive scrapes within Wales during 2007 (mean of 17.8 positive scrapes per region). The count in England and Scotland remained low (n = <14). In 2013 (Figure 2.6 C), a decrease in the number of positive scrapes occurred across the country, with a maximum of 11 positive scrapes in any region, observed in Ceredigion. In 2018, the low counts (n = <7) remained across England and Scotland (Figure 2.6 D); however, counts in Wales varied from 4 in North East Wales to 27 in Carmarthenshire.

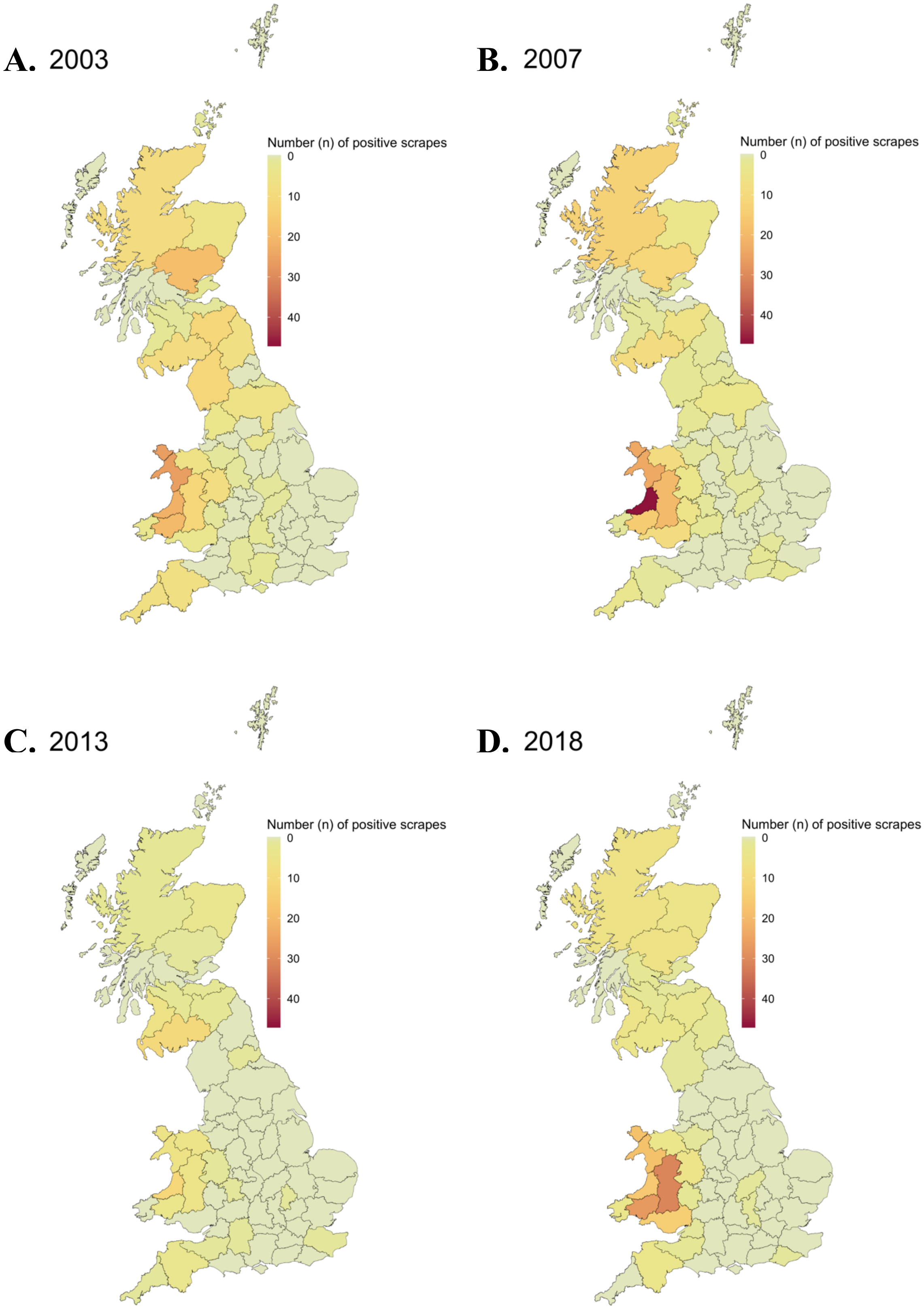


Figure 2.6: *Spatial distribution of VIDA positive scrapes in Great Britain for four key years in the 2003-2018 study period: A) 2003, B) 2007, C) 2013 and D) 2018.*

Table 2.3: *The ten regions with the highest totals of positive scrapes across 2003-2018.*

Region	**Country**	**Total**
Ceredigion	Wales	378
North West Wales	Wales	279
Carmarthenshire	Wales	189
Powys	Wales	188
Highlands	Scotland	121
Dumfries & Galloway	Scotland	120
Tayside	Scotland	103
Scottish Borders	Scotland	82
North Eastern Scotland	Scotland	75
South Wales	Wales	68

2.3.4. Sheep scab initiatives

Within the study period, 11 targeted sheep scab disease control initiatives, as described in Table 2.4, took place between 2003 and 2018 across GB: 4 in Wales, 3 in England and 4 in Scotland.

Wales

In Wales, all four initiatives were categorised as 'free testing'. The details of the first APHA free testing initiative (operating from 1st December 2003 to 28th February 2004), the Hybu Cig Cymru (HCC)/Meat Promotion Wales and sheep scab ELISA validation were all similarly sourced from personal correspondence (Table 2.4). As such, no official report was available on the results of these initiatives. However, a report was available for the second period of APHA free testing (from 20th December 2017 to 31st March 2018) (APHA, 2018a), which outlined the intended aims and results of this period of free testing (Table 2.4).

England

England shared two of its three initiatives with Wales: the APHA free testing (from 1st December 2003 to 28th February 2004), and the sheep scab ELISA validation free testing (Figure 2.7). The third, instead, was an industry-led 'knowledge transfer & skills training' initiative named "Stamp out Scab", which operated for 15 months. The details of the two initiatives shared with Wales were similarly obtained from personal correspondence (Table 2.4). Information about the aims and workshops delivered to veterinarians and Registered Animal Medicines Advisors (RAMAs) as part of the "Stamp out Scab" campaign was obtained from the advertising material and previous literature (Table 2.4).

Scotland

Uniquely, Scotland offered its initiatives continuously throughout the study period (Figure 2.7). For the first 8 months the SRUC offered free diagnostic tests for sheep scab, similar to the APHA free testing initiatives. Then, the Scottish Sheep Scab Initiative (SSSI) was introduced as a result of industry pressure to control sheep scab. This was led by industry and government, offering advice on best practice coupled with free testing to increase awareness of sheep scab (Table 2.4). After the SSSI ended, the SRUC free testing resumed and a working group was formed to pave the way towards developing legislation, the Sheep Scab (Scotland) Order 2010. This reintroduced sheep scab as a notifiable disease in Scotland, mandating the reporting of suspected cases (SRUC, 2018; The Scottish Government, 2010).

Table 2.4: *Description of the targeted national sheep scab disease control initiatives that occurred between the 1st January 2003 and 31st December 2018 across GB. ADAS = Agricultural Development Advisory Service, APHA = Animal and Plant Health Agency, AHDB = Agriculture and Horticulture Development Board, HCC = Hybu Cig Cymru / Meat Promotion Wales, RAMA = Registered Animal Medicines Advisor, RDPE = Rural Development Programme for England, SHAWG = Sheep Health and Welfare Group, SRUC VS = Scotland's Rural College veterinary services*

Initiative Name / Organisation	**Start Date**	**End Date**	**Initiative Type**	**Description**
Wales				
APHA	1st December 2003	28th February 2004	Free testing	Period of free skin scrape testing funded and operated by the APHA, operated across England and Wales (*S Mitchell, personal communication).*
HCC/ Meat Promotion Wales	1st January 2007	28th February 2007	Free testing	Period of free skin scrape testing funded by HCC, an industry-led levy board (*S Mitchell, personal communication).*
Sheep scab ELISA validation	1st April 2015	1st September 2015	Free testing	Period of free testing initiated by the APHA inviting the submission of a skin scraping and blood sample for the validation of the sheep scab ELISA. (*S Mitchell, personal communication).*
APHA	20th December 2017	31st March 2018	Free testing	Period of free testing funded by the Welsh Government and operated by the APHA, after the first reported cases of resistance to macrocyclic lactones were identified (Doherty et al., 2018).
England				
APHA	1st December 2003	28th February 2004	Free testing	Period of free skin scrape testing funded and operated by the APHA *(S Mitchell, personal communication).*

Stamp out Scab	1st January 2013	31st March 2014	Knowledge transfer & skills training	Initiative aimed at knowledge transfer (facilitated by RAMAs for dissemination to clients) and skills training (sessions provided by ADAS veterinarians), instigated by the AHDB and funded through the RDPE (ADAS, 2013; Phillips et al., 2013).
Sheep scab ELISA validation	1st April 2015	1st September 2015	Free testing	Period of free testing initiated by the APHA inviting the submission of a skin scraping and blood sample for the validation of the sheep scab ELISA. (*S Mitchell, personal communication).*
Scotland				
SRUC VS	1st January 2003	10th September 2003	Free testing	Period of free skin scrape testing funded and operated by the SRUC (SRUC, 2018)
Scottish Sheep Scab Initiative	11th September 2003	31st December 2006	Knowledge transfer & free testing	A largely industry-led, 3-year long initiative launched at Kelso ram sales (Hosie, 2003) initiated by NFU Scotland towards increasing awareness of sheep scab and promoting best practice in disease control through the provision of information (ADAS, 2008).
SRUC VS	1st January 2007	16th December 2010	Free testing	Period of free skin scrape testing funded and operated by the SRUC (SRUC, 2018).
Sheep scab (Scotland) Order 2010	17th December 2010	*Ongoing*[1]	Legislation	Mandated the notification of holdings with or suspected to have sheep scab to the local APHA office (The Scottish Government, 2010).

[1]As of September 2020

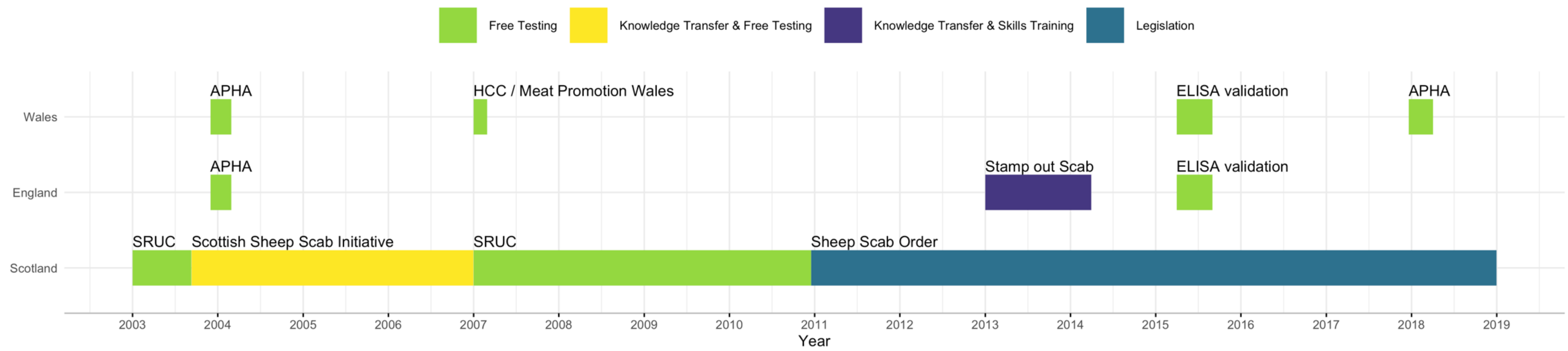


Figure 2.7: *Timeline of the targeted sheep scab disease control initiatives from 2003-2018 across GB, which includes free testing (green), knowledge transfer & free testing (yellow), knowledge transfer & skills training (purple), and legislation (blue). For description of initiatives see Table 2.4.*

2.3.5. Aberration detection

The TADA was applied separately for each country due to the devolved nature of animal health in GB, which has been shown to apply to sheep scab through the largely devolved initiatives (Figure 2.7), and differences in counts and trends of each country (Figure 2.2).

The baseline period used for England ran from week 1 of 2006 to week 52 of 2009. A later starting reference period was used due to high counts being observed at the beginning of the study period compared with later years as seen in Appendix 3A, and also taking into consideration the APHA period of free testing from 1st December 2003 to the 28th February 2004 (Figure 2.7). Therefore, the study period analysed by the TADA was from week 1 of 2010 to week 52 of 2018. The TADA raised one alarm during the study period (Figure 2.8). The alarm was raised in week 39 of 2010 (week beginning 27th September), when 4 positive scrapes were diagnosed, exceeding the upper boundary of 3.45 predicted positive scrapes (Table 2.5) and also representing the highest count of the weekly time-series for England. This alarm occurred outside the time period of any of the regional initiatives (Figure 2.7).

For Wales, the period of APHA free testing was also excluded from the baseline period, as it was for England. Due to a higher number of counts per week in Wales opposed to England and Scotland (Appendix 3), convergence of the model was achieved with a shorter baseline period of 2.5 years, from week 27 of 2004 to the end of 2006. Therefore, the TADA was applied across week 1 of 2007 to the end of 2018. This allowed the TADA to evaluate three of the four initiatives that occurred across the study period.

The TADA for Wales raised 15 alarms (Figure 2.9) from 2017 to 2018. In total, 11 of the 15 alarms (73.3%) occurred from December 2017 to March 2018, falling within the APHA free testing initiative period. The other four alarms did not align with any other known national initiatives. The counts observed on weeks with alarms, compared to the upper threshold produced by the model are displayed in Table 2.5. The highest number of positive scrapes occurring in one week was 16, on the week beginning 15th January 2018. Also, with the exception of two alarms, all alarms occurred in either winter or spring (Table 2.5).

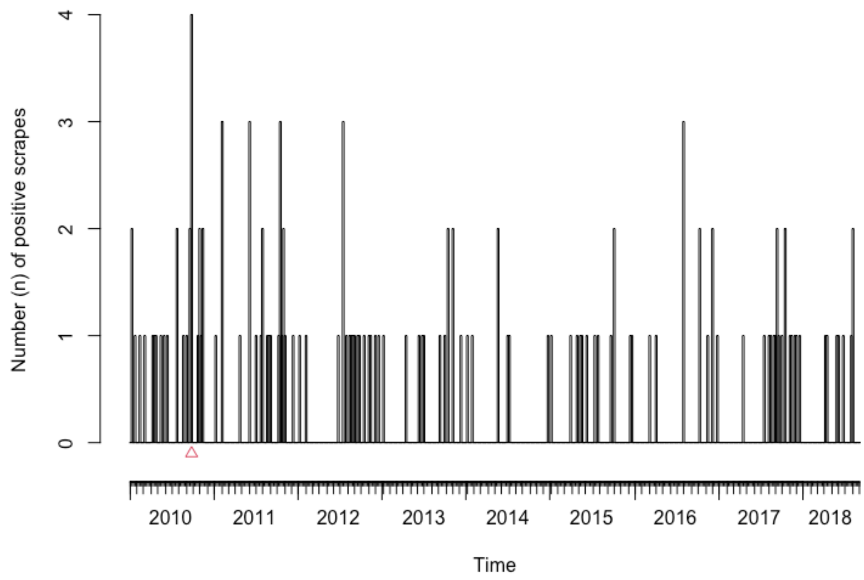


Figure 2.8: *Time-series plot with a temporal aberration detection algorithm (TADA) applied for the count of Veterinary Investigation Diagnosis Analysis (VIDA) positive scrapes in England from week 1 of 2010 to the end of 2018, using a reference period of week 1 of 2006 to the end of 2009. Red triangles indicate alarms raised by the TADA, showing a significant deviation from the expected count.*

Scotland offered initiatives throughout the study period, hence including these in the baseline period was unavoidable. However, the baseline period was adapted to minimise any initial effect from the start of the SSSI. The baseline used was the 4-year period from week 1 of 2005 to the end of 2008, therefore allowing for analysis using the TADA from the start of 2009 to the end of 2018. The TADA yielded four alarms, two in 2010, one in 2015 and one in 2016 (Figure 2.10). Of the two alarms raised in 2010, the second was raised in week 51, beginning the 20th December, the week after the introduction of the sheep scab order (Figure 2.7).

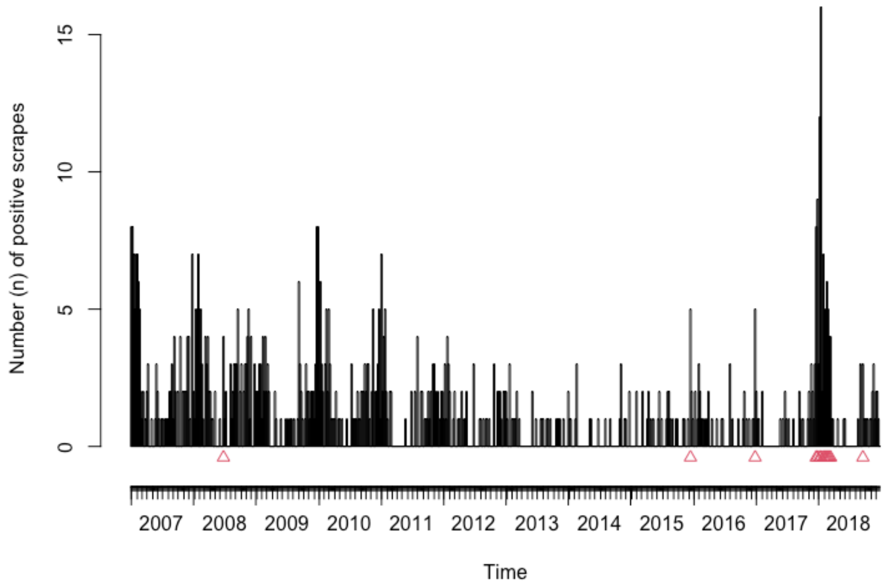


Figure 2.9: *Time-series plot with a temporal aberration detection algorithm (TADA) applied for the count of Veterinary Investigation Diagnosis Analysis (VIDA) positive scrapes in Wales from week 1 of 2007 to the end of 2018, using a reference period of week 27 of 2004 to the end of 2006. Red triangles indicate alarms raised by the TADA, showing a significant deviation from the expected count.*

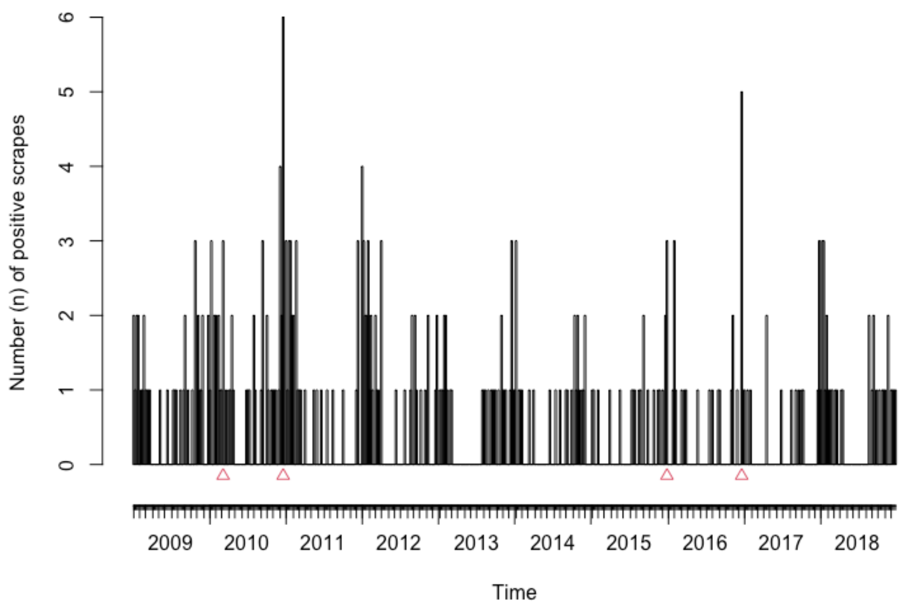


Figure 2.10: *Time-series plot with a temporal aberration detection algorithm (TADA) applied for the count of Veterinary Investigation Diagnosis Analysis (VIDA) positive scrapes in Scotland from the beginning of 2009 to the end of 2018, using a reference period from the beginning of 2005 to the end of 2008. Red triangles indicate alarms raised by the TADA, showing a significant deviation from the expected count.*

Table 2.5: *Alarms raised by the temporal aberration detection algorithm (TADA) applied to England, Wales and Scotland. Periods monitored: England 2010-2018; Wales 2007-2018; Scotland 2009-2018. Week is the week number in accordance with the ISO 8601 standard. The upper threshold is the number of counts, as determined by the TADA, which would need to be exceeded before an alarm is generated.*

Country	**Alarm date**		**Count of positive scrapes**	**Upper threshold**
	Year	***Week***		
England	2010	39	4	3.45
Wales	2008	26	4	3.83
	2015	51	5	3.75
	2016	52	5	3.78
	2017	51	8	4.24
	2017	52	9	4.24
	2018	2	12	4.96
	2018	3	16	4.44
	2018	5	7	3.63
	2018	6	4	3.36
	2018	7	5	3.37
	2018	8	6	3.37
	2018	9	5	3.65
	2018	10	4	3.14
	2018	11	4	2.34
	2018	38	3	2.67
Scotland	2010	10	3	2.96
	2010	51	6	5.35
	2015	53	3	2.64
	2016	51	5	4.07

2.4. Discussion

As with many endemic diseases in GB, sheep scab will not be eradicated without considerable effort and long-term commitment from all stakeholders, requiring a high level of investment from both the government and the industry. This is further complicated by the highly variable prevalence of this disease within the country. Therefore, the development of targeted, sustainable and cost-effective strategies is paramount to the future success of disease control. In this chapter, one of the aims was to investigate an existing data source for the scanning surveillance of sheep scab in GB (the VIDA database), to identify current trends and geographical "hotspots" for sheep scab. In contrast to previous studies which indicated an increasing or stable prevalence (Bisdorff et al., 2006; Chivers et al., 2018; Rose et al., 2009), data in this study showed a decline in the annual counts of positive scrapes in all countries of GB, with the exception of 2018. The monthly distribution of positive scrapes was similar to the expected seasonality for sheep scab (French et al., 1999), and the spatial distribution of positive scrapes also displayed a pattern comparable to previous studies, with high counts observed in Wales, northern Scotland and northern England. This would suggest prioritizing these areas for future targeted control strategies. While these raw counts cannot be used to infer disease prevalence, the application of a denominator, as the ones proposed here, could aid interpretation of these counts.

The deregulation of the mandatory organophosphate sheep dipping saw the prevalence of sheep scab in GB increase to an endemic level (Nieuwhof and Bishop, 2005). More recently however, results from a postal study in Wales suggested the prevalence had remained stable over the past 10 years (Chivers et al., 2018). Here, the count of positive scrapes significantly decreased across the 16 years, a similar trend observed in all three potential denominators (Figure 2.4). This strongly supports the hypothesis that the prevalence of sheep scab has remained relatively stable over the study period, while the submission of diagnostic samples has reduced, impacting on the overall count of positive scrapes. This could be explained by fewer confirmatory diagnoses being sought by vets and farmers. As holdings which previously had sheep scab outbreaks have been shown to be significantly more likely to have further outbreaks (Rose et al., 2009), once the disease has been diagnosed farmers may opt to treat any subsequent outbreaks without investigating further. The reduction in the submission for diagnostic sampling may also be influenced by the cost, which currently stands at £24.70 per ectoparasite screen excluding any veterinary call out fees in England and Wales (APHA, 2020b). This is a particular concern for hill and upland flocks where only the top producers make any net profit (Harvey and Scott, 2020; Quality Meat Scotland

[QMS], 2017). In Scotland, the submission of ectoparasite screens for suspected sheep scab cases has been free since 2002 (SRUC, 2018), so the decision to submit samples for testing is unlikely to have such financial bearing. In addition, the closure of some VICs across England and Wales in 2013 and 2014 (*Veterinary Record*, 2011) may have influenced the willingness of veterinarians to submit samples to the APHA for diagnosis. Sheep scab is diagnosed by the APHA and SRUC through the submission of samples which can be posted, and while this effect should have been minimal, the loss of the relationships formed between centres and veterinarians (House of Commons Environment Food and Rural Affairs Committee, 2011) may have caused a more significant decline. Finally, over time, veterinary practices may have opted for an increase of in-house or on-location testing of samples. These results are currently lost from a surveillance point of view.

Somewhat unexpected after the sustained annual decline, was the substantial increase in positive scrapes in 2018, to 2.5 times the counts of the previous year. In Wales, the APHA free testing initiative which occurred from December 2017 to March 2018 (Table 2.4) saw a 500% increase in submissions (APHA, 2018b), and likely contributed significantly to this increase. However, no known initiatives were employed during this time in England and Scotland. Therefore, the increase may have been a residual effect from increased awareness of sheep scab as a result of promoting the welsh scheme (APHA, 2018a), or due to regional disease awareness campaigns after the first reported cases of resistance (Doherty et al., 2018), which were not captured in this study (French et al., 1999).

The "hotspots" (areas with high numbers of confirmed cases) identified in the VIDA data were similar to previous studies, with high counts occurring in Wales and northern Scotland (French et al., 1999; Rose et al., 2009). This could support the use of the VIDA database as a suitable means of scanning surveillance, creating a continuous evidence-base for the targeting of disease control initiatives. With further refinement of the geolocators (for example to a parish level), the spatial distribution of positive scrapes could aid the development of localised control programmes.

One of the commonly reported challenges for the use of the VIDA database to inform prevalence is the submission bias. As a diagnostic database, submissions of suspected cases are made voluntarily, and thus might not be representative of the total population at risk. This introduces an important source of selection bias, as submission might be influenced by different factors, like geographical location, awareness and attitudes towards the disease, economic values (of both the disease and animals), the density of animals in an area, and the number of animals affected (APHA, 2019a). Consequently, the number of positive scrapes might not represent the true prevalence of the disease; however, these data are considered of high quality due to the rigorous quality of the test from the UKAS accreditation. To account for the spatial distribution of sheep scab in relation to the sheep population, a denominator such as total sheep population from the yearly June agricultural census (National Statistics, 2019) or density of sheep per holding could be applied to the positive scrapes. These denominators could help highlight additional "hotspot" areas where the sheep population might be small, but many animals are infested (CDC, 2020). It would also help to differentiate between areas of low disease burden despite having a high density of sheep population versus areas with a low density of sheep population. In this study, for example, eight regions (six in England and two in Scotland), had zero positive scrape diagnoses between 2003 and 2018. Some of these areas may be highly industrialised with low density sheep populations which could explain the lack of sheep scab diagnoses, but in others, it could represent a low presence of disease. As mentioned before, geographical locations can also have a significant impact on submission of diagnostic samples. In the case of Eileanan an Iar (the Western Isles off the north west coast of Scotland), since the introduction of the Sheep Scab (Scotland) Order in 2010, the Scottish Government reported 32 sheep scab notifications in this region between 2010 and 2019 (APHA, 2020b), yet no positive scrapes were recorded in the VIDA database. Therefore, this suggests that diagnoses have either not been pursued or are confirmed in a different way (e.g. through private veterinarians). It is, however, important to highlight here that these are very different datasets; with the Scottish Government notification data holding a record of suspected cases, and the VIDA database only confirmed positive diagnoses. Yet, there is no particular incentive for farmers to raise a notification for sheep scab if the disease is not present. However, from both databases it is clear that sheep scab is likely vastly underreported in GB, which may be at least in part due to the historic but still present stigma towards the disease among the farming community.

Since denominators such as total sheep population were not easily accessible for use in this study and would not be continuously available for the interpretation of the positive scrapes, alternative denominators were sought from the VIDA database itself to enhance the interpretation of the positive scrapes. The total diagnostic submissions dataset offered an insight into the number of diagnostic submissions made across the SRUC VS and the APHA, but positive scrapes represented only a very small proportion of the total submissions due to the number of other diagnoses made which are included in the VIDA database. However, it is important to have an awareness of the overall trends in diagnoses being made when interpreting the positive scrape data, to understand external factors which may have influenced the overall submission rate, such as the VIC closures in 2013 and 2014. In contrast to the number of submissions in the total diagnostic submissions, the count of submissions in the scrape submissions dataset was predominantly lower than the number of positive scrapes. This demonstrates that this dataset does not incorporate all sources from which sheep scab diagnoses are being made, and as such does not offer a suitable denominator to contextualise the number of positive scrape submissions. The skin submissions and scheduled scrapes datasets both related well to the annual pattern of sheep scab diagnoses, and therefore either could potentially be applied as a denominator to contextualise the number of positive scrapes. The main difference between these denominators was that the skin submissions dataset represents all submissions where the presenting complaint was listed as skin problem by the submitting private veterinarians, and the scheduled scrapes dataset was the number of tests scheduled by the VIO to diagnose suspected sheep scab. The skin submissions dataset, as a denominator, could, therefore, determine (i) the proportion of positive sheep scab submissions in the context of overall submissions with suspected skin diseases and (ii) whether other ectoparasites were involved when sheep scab was suspected. From this study, almost 30% of the skin submissions were positive for sheep scab, which confirms sheep scab as a significant problem in the context of skin diseases in sheep. By analysing the dataset for other VIDA codes, further insight into other ectoparasites (i.e. lice) as a differential diagnosis for sheep scab could be available. Meanwhile, scheduled scrapes included all diagnostic tests conducted to diagnose suspected sheep scab, so is likely more appropriate when considering the proportion of suspected cases which were eventually diagnosed as positive, and perhaps more importantly, negative. In this study, 46% of the scheduled scrapes were positive and, as such, over half of the tests conducted were negative. This highlights that even when sheep scab was suspected, it was more than half of the time not diagnosed. The application of these datasets as potential denominators share similar caveats as they cannot be used to infer prevalence (they are not representative of the population at risk). However, the use of these denominators is valuable to contextualise the counts of positive scrapes. Furthermore, both of these denominators were easily extracted from the database and share the same format as the positive scrapes. This made their analysis significantly easier than other datasets, and thus would promote their continued use as suitable denominators.

The second aim of this chapter was to investigate the impact of past disease control initiatives and therefore give recommendations for their future use. The information about the sheep scab control initiatives described here were only available through the organisation(s) that coordinated them, or from personal correspondence. With the exception of results from the

APHA free testing in December 2017 to March 2018 being published in a quarterly disease surveillance report (APHA, 2018b) and a survey measuring the impact of the SSSI (ADAS, 2008), information on the outcome on the majority of initiatives was unavailable and thus made it impossible to determine whether these initiatives were successful without first-hand experience. It was also often difficult to locate information which pertained to the operational dates or original objectives of the initiatives as sources were not available publicly. This study has highlighted that there is considerable value in retaining details about these events in the public domain, not only to avoid specific knowledge being only available to the coordinating organisations (and often only to a few people) but also to avoid this knowledge being lost or forgotten. Therefore, to facilitate a more effective approach to information storage about sheep scab control initiatives, it may be beneficial to consider instating a UK-wide database, similar to the USA's centers for disease control and preventions (CDCs) list of national health initiatives which covers a range of diseases important to human health (CDC, 2020). In addition to compiling information on past initiatives, if used prospectively for activities still in the planning phase, a database could encourage support from other stakeholders. This could ultimately offer a more cost-effective alternative by increasing the impact of each individual disease control programme. Currently, the adoption of a database could be particularly valuable between England and Wales, where control strategies have in the past been very similar.

The impact of the initiatives was measured using a TADA, a technique commonly used to detect outbreaks of pathogens in healthcare settings (Yuan et al., 2019). Limited previous work has been conducted to investigate the impact of different types of disease control initiatives (ADAS, 2008); however, the application of the TADA could offer a near real-time evaluation. A number of TADAs, including the original Farrington (Farrington et al., 1996), improved Farrington (Noufaily et al., 2012), CUSUM, and negative binomial (Salmon et al., 2016), were considered for this study. Ultimately, the original Farrington method was selected as it worked well for highly seasonal data and allowed a shorter baseline period for the model training before convergence was achieved. This was required to minimise the potential aberration within the baseline periods and maximise the number of initiatives which could be studied. However, the original Farrington methodology does not account for sustained shifts in the counts, which could have increased the sensitivity of the model. The performance of each TADA is also highly reliant on the quality of the baseline period supplied. This was very much variable for each country due to conflicts with initiatives, and high counts at the beginning of the study period which prevented model convergence, notably for England's TADA (Figure 2.8). In addition, it is possible that aberrations occurred during the baseline which were not known, thus could not be accounted for.

The most common initiatives for targeted sheep scab disease control were 'free testing' initiatives, which accounted for 8 out of 11 initiatives. The majority of resulting aberrations aligned with one period of APHA free testing from December 2017 to March 2018 in Wales, which indicates that free testing provoked an increase in diagnostic submissions, achieving one of the main goals of these kind of initiatives. Compared to all of the other sheep scab initiatives in this context, free testing is much easier to implement and coordinate and, above all, offers a cost-effective way to increase testing at a specific point in time. This suggests that free testing is a suitable way to capture the initial interest from farmers, but more often, only long-term education through knowledge transfer or knowledge exchange can produce lasting changes in mindset and behaviour (O'Kane et al., 2017) that could ultimately decrease the incidence of sheep scab. However, as shown, the impact of knowledge transfer activities is more difficult to quantify. No aberrations specifically aligned with initiatives such as 'Stamp out Scab' where the initiative type was 'knowledge transfer & skills training'. This was likely as the aim of this initiative was not to directly impact the number of submissions but to increase the overall awareness of the disease instead. As such, even though knowledge transfer activities require much more coordination, incur significant cost, and require significantly more commitment from all involved, they should not be discontinued. In future, to effectively measure their impact, alternative methods such as the survey conducted after the SSSI (ADAS, 2008) which measured overall awareness of the initiative, could be adopted to complement the use of the TADA.

Concerning the TADA, Scotland was in a unique position with initiatives in place throughout the study period. Therefore, the baseline period had to be set within the SSSI, which likely meant a higher baseline than expected. Despite this, alarms were still generated: one at the introduction of the new legislation, and a further two within the notifiable period, suggesting the alarms generated may be representative of true aberrations. The pressure to achieve sheep scab control in Scotland has been predominantly led by industry, which shows that there was a desire in the country to achieve control of sheep scab. Ultimately, this pressure led to the creation of the notification status. Even so, the notifiable status on its own is unlikely to result in eradication. Continuous and active strategies such as knowledge transfer will need to be adopted on top of this to maintain the desire to reach eradication and increase the knowledge about as the initiatives caused an increase in positive scrapes sheep scab.

To summarise, the impact of free testing and legislation initiatives could be measured with the TADA analysis as the initiatives caused an increase in positive scrapes. The further use of this method is therefore promising for the application to other endemic diseases and takes into consideration a number of factors including prevalence, awareness, economic burden, and current disease control methods.

In conclusion, the further analysis of the existing scanning surveillance source, the VIDA database, enhanced our knowledge of sheep scab by identifying potential "hotspot" areas for targeted disease control initiatives. It shows a decline in overall submissions, strong seasonal pattern and confirmed that Wales in particular is an area to focus on for future control efforts. Furthermore, two alternative denominators (skin submissions and scheduled scrapes) extracted from the VIDA database itself, have potential value for the further interpretation of positive scrapes. Finally, the TADA offered a framework to objectively measure the impact of targeted disease control initiatives, something that is being advocated widely as a more cost-effective and sustainable approach to the long-term control of endemic diseases and as a complementary tool in scanning surveillance.

3. Evaluating the use of commercial diagnostic data to enhance the scanning surveillance of sheep scab

3.1. Introduction

The integration of new data sources is being increasingly recognised as a potentially cost-effective strategy to add value to the existing scanning surveillance for many diseases, particularly endemic diseases (Middlemiss et al., 2018). The scanning surveillance of sheep scab is currently achieved through the VIDA database, as discussed in Chapter 2; however, the recent commercialisation of the sheep scab ELISA may present new opportunities to inform control strategies.

As previously described in 1.2.3.1, the sheep scab ELISA offers a new approach to the diagnosis of sheep scab versus the conventional skin scraping methodology, using blood samples to provide a highly sensitive and specific diagnosis of sheep scab at a clinical and subclinical level (Burgess et al., 2012). The sheep scab ELISA can be applied to diagnose individual sheep, but also provides a powerful estimation of serostatus at a flock level using a 12-sample screening, even with low mite burden (Hamer et al., 2019). This has particular value for monitoring flocks as part of a proactive disease management strategy. The sheep scab ELISA detects a rise in antibody levels to the *Pso o 2* allergen as early as 2 weeks post infestation, and thus is able to detect subclinical cases several weeks before clinical signs develop (Burgess et al., 2012). Furthermore, the retesting of flocks 10 days post-treatment can show decreasing antibody titres to prove efficacious treatment, which could be particularly valuable with the emergent resistance (Hamer et al., 2019).

To prevent outbreaks and guide the management of sheep scab, as with most diseases, it is also important to consider factors which may impact the risk of transmission. For sheep scab it has previously been shown that the use of common grazing (where multiple holdings graze their sheep on the same land without boundaries) resulted in a significantly higher prevalence of sheep scab and an increased chance of repeated outbreaks (Cross et al., 2010; Rose and Wall, 2012). In addition, land at a higher altitude has been shown to have a higher prevalence of sheep scab than lower altitude (Vineer, 2011). Current guidance to reduce the transmission of sheep scab includes recommending good general biosecurity, such as minimising contact with neighbouring animals through the use of double fencing, minimising shared facilities, and the use of contractors for dipping and shearing (ADAS, 2008). However, there is currently little scientific evidence surrounding the impact of many of these, often costly, biosecurity measures for sheep scab.

Using data from the recently commercialised sheep scab ELISA diagnostic test, this chapter aims to enhance our knowledge and understanding for the scanning surveillance of sheep scab. Through digitisation of all data from the sheep scab ELISA, it aims to provide a new usable source of data. It then aims to use this data to provide information on the current use and uptake of the sheep scab ELISA and investigate the risk associated with certain management practices. Finally, this chapter also aims to consider the potential value of the sheep scab ELISA data as an additional source of scanning surveillance.

3.2. Materials and methods

3.2.1. Data collection and collation

3.2.1.1. Data description

Biobest Laboratories Ltd ("Biobest") is a commercial laboratory based near Edinburgh, Scotland, that specialises in diagnostic testing for infectious diseases in both livestock and companion animals. In February 2017 they commenced operation of a sheep scab antibody ELISA test (herein referred to as 'sheep scab ELISA'), which was developed at Moredun Research Institute (MRI). As of September 2020, Biobest were the only company operating the sheep scab ELISA in the UK.

All samples submitted to Biobest from one holding are defined as a submission, therefore a single submission can contain any number of blood samples. As the test is designed primarily to detect subclinical cases and for monitoring purposes, 12 blood samples should be drawn from individuals within each flock or management group (separate groups of sheep on the same holding). This is based on previous statistical analysis, providing a powerful estimation of the serostatus at the flock level for flocks/management groups of up to 2,000 animals (Hamer et al., 2019) i.e. whether the whole flock/group should be considered infested (positive) with sheep scab or not (negative). Each submission and its corresponding laboratory results are linked by a 6-digit unique identifying code, and each sample within the submission is distinguished by a 7-digit unique identifying code.

Two datasets were available for this research: the 'submission forms' and 'result report'. The submission forms, an example of which is displayed in Appendix 4, consist of two A4 sides of questions. These are received by the laboratory as a hand-filled paper copy accompanying each submission, with the purpose to offer information for interpretation of the results report. For long-term storage of the submission forms, they are scanned and added to a rolling PDF document which captures all submission forms submitted to the laboratory. The results report is a PDF document extracted from Biobest's Laboratory Information Management System (LIMS). The report captures all of the individual sample results (distinguished by their 7-digit unique identifying code) for the sheep scab ELISA grouped by the submission's 6-digit unique identifying code, as shown in Appendix 5. All samples are tested in duplicate; therefore, the result for each sample is an average of the optical density (OD) observed in each well. When the variance between OD results exceeded 20%, samples were retested. Therefore, on some occasions more than one result was reported for a single sample.

3.2.1.2. Database creation

Before September 2019 (the start of this project), no database existed that collated the submission forms and result report. Therefore, the data were manually digitised from the PDF files. Data were captured from both datasets from the 1st February 2017 to the 31st August 2019, a period of 31 months.

As a first step, data from the results report were recorded in a Microsoft Excel spreadsheet. This totalled 4 fields: the date of reporting, the 6-digit unique identifying code for the submission, the 7-digit unique identifying code for the sample, and the associated OD result(s) for each sample. Each result report also included a written interpretation of the OD results, written by the veterinary staff at Biobest (data not captured), which assessed the flock's or management group's serostatus based on the OD values and answers to the submission form fields. Then, the data from the submission form, totalling 35 fields (as detailed in Appendix 6), were digitised from the original PDF and recorded in a further Microsoft Excel spreadsheet.

3.2.1.3. Data cleaning

After collation, the data were cleaned to unify terminology, fix misspellings, and correct the formatting of certain variables (i.e. dates) in order to prepare them for analysis. Due to lack of information as submission forms were not completed, 209 of the 542 submissions forms were excluded from the analysis.

For 20 of the 3,089 samples analysed more than one OD result was recorded. To avoid duplication, only one result was analysed for each sample. In these cases, the sample result selected was determined by making use of the written interpretation from the original result report (described in 3.2.1.2).

To locate the geographical provenance of the samples, two fields, 'holding number' and 'postcode' were captured from the submission form (Appendix 6). The holding number, also known as the county-parish-holding number (CPH), is a unique 9-digit number given to each holding that is registered to keep livestock. The first two digits pertain to the county, the next three to the agricultural parish, and the final four digits to the unique holding within the agricultural parish (e.g. 01/001/0001). For the purposes of our analysis and to maintain anonymity, the holding numbers were retained to the agricultural parish level only (first 5 digits). The holding numbers were then used to obtain spatial coordinates (longitude and latitude) from the APHA's parish shapefile (as in Chapter 2). Similarly, postcodes are a 5 to 7-digit alphanumeric code split in two halves, one of 2-4 digits, the other with 3 digits, which defines a specific location for mail deliveries in the UK, often with several properties sharing one postcode. The first 1 or 2 digits of the postcode defines a particular region, e.g. IV = Inverness. The remaining digits (numerals) within the first half pertain to a specific part of the region, and the last half further refines the location to the street. To obtain the spatial coordinates of the submission from the postcode, the publicly available ONS's National Statistics Postcode Lookup from February 2019 (Office for National Statistics, 2019a) was used. If both the postcode and holding number were available for a submission, the postcode was chosen in preference due to increased location accuracy.

Of the 35 fields digitised from the submission forms, four ('contract shearing', 'contract dipping', 'shared gathering facilities' and 'shared livestock trailers') required the farmer or veterinarian to circle any of the options that applied to the holding. As no escape option to opt out from these categories (e.g. 'other – please specify') was provided, all types of marking (e.g. circle, striking a line etc.) were considered a positive response. If no mark was applied to the specific question, but the submission form was otherwise well completed, this was interpreted as a negative response.

3.2.2. Data analysis

All databases were created in Microsoft Excel 365. All analyses and visualisations, unless otherwise stated, were performed in R version 4.0.0 and RStudio.

3.2.2.1. Calculated serostatus

Individual sample results are categorised at Biobest into three possible outcomes dependent on their OD: negative, suspect, or positive (see Table 3.1). Where single samples are submitted, this is considered the final result (serostatus). Where multiple samples are included in a submission, interpretation of the single results to provide the overall submission serostatus is achieved using the information from the submission form and, ultimately, the judgement of the experienced Biobest veterinarian. However, this research project is part of a wider collaborative network (DEFRA – Lot 2 Antiparasitic Resistance: Sheep Scab) among which a standardised dichotomous interpretation of submission serostatus has been developed (Innocent, G., *unpublished*). Therefore, this newly developed framework has been applied here to provide an interpretation of the sample results within each submission, irrespective of the number of samples included within the submission.

Table 3.1: *Cut-off values used to determine the serostatus of individual samples. The result is the average OD value from duplicates of the sample, multiplied by a factor of 100.*

OD Result	Interpretation
≤ 39	Negative
40-49	Suspect
≥ 50	Positive

The new framework uses a Bayesian approach allowing the inclusion of prior knowledge about the animal's probability of having a positive result, combined with the test result to provide a posterior probability that it is positive. This is calculated as:

$$P_{(positive|test\ result)} = \frac{P_{(positive)} \times P_{(test\ result|positive)}}{P_{(test\ result)}}$$

The prior, denoted as *P(positive)*, is the probability that the animal is positive without a test and is calculated using existing knowledge about the animal's individual risk of disease. The prior value is multiplied by *P(test result | positive),* which is the probability of the test result if that animal is positive, directly calculated from a distribution of positive test results from animals with known serostatus. *P(test result)* is the probability of the test result, calculated as *P(test result | positive)P(positive) + P(test result | negative)P(negative),* where *P(test result | negative)* is directly calculated from a distribution of negative test results from animals with known serostatus, and *P(negative)* as the prior probability that the animal is negative without a test (Innocent, G., *unpublished*).

The above method was used to interpret the probability of an individual sample testing positive using a prior value of 0.1, assuming a 10% prevalence of sheep scab in the UK (Bisdorff et al., 2006). Then, this was converted to a submission level serostatus (where multiple samples were included in a submission) by calculating the mean of posterior values for all samples within each submission. A cut-off threshold was then applied to determine whether the submission was positive or negative, calculated as 1/2n, where n is the number of samples in the submission. If the mean of the posterior values for the submission was higher than the chosen threshold, the flock serostatus was interpreted as positive, and if it was lower it was interpreted as negative.

3.2.2.2. Descriptive analysis

The date captured from the result report was used to visualise the temporal pattern of the sheep scab ELISA submissions per month since its commercialisation. Then, to assess whether the sheep scab ELISA was used primarily as a tool for flock screening (submissions of 12 samples) or for individual diagnosis, the number of blood samples within each submission was aggregated into groups (from '1' to '12' samples in a submission). Any submissions containing more than 12 samples were grouped together into a further category, '>12'.

Using spatial coordinates from the submission forms (as previously described in 3.2.1.3), a descriptive spatial analysis was performed to visualise the spatial distribution of submissions since the commercialisation of the sheep scab ELISA. Points were plotted on a UK shapefile obtained from the Office of National Statistics, at Nomenclature of Territorial Units for Statistics (NUTS) level 2 (Office for National Statistics, 2019b). Each individual point was coloured based on the calculated serostatus as described in 3.2.2.1, red for positive and blue for negative. For two remote holdings, the points were moved to the nearest populated area to avoid identification.

To evaluate the completeness of the submission forms, all fields were counted, divided by the total number of submission forms and multiplied by 100 to produce a percentage. To establish whether there was a significant difference between the completion of the two pages, the completion rates of page 1 were compared with page 2 by performing a two sample t-test.

To further explore the use of the sheep scab ELISA, the 'farm type' and 'reason for testing' were analysed. The 'farm type' refers to the primary land type of the holding. Three farm type categories: 'lowland', 'upland' and 'hill', were presented as options to circle. If multiple options were circled, they were categorised into an additional 'mixed' category. Meanwhile, the 'reason for testing' is why the holding submitted for sheep scab ELISA testing. On the submission form the reason for testing field included four options: itchy, monitoring, quarantine, or other. However, within the 'other' category (a free text area), two further reasons for testing ('wool loss' and 'retest') presented multiple times, so were used as additional categories, as shown in Table 3.2. Then, to establish whether the farm type had an effect on the reasons for testing, the reasons for testing were visualised as a proportion of the total submissions for each of the four farm type categories.

Table 3.2: *Options for "Reason for testing" available in the submission form and their description*

Reason for Testing	Description
Itchy	Samples are submitted for the diagnosis of itchy animals (i.e. animals with clinical signs of sheep scab).
Monitoring	Samples are submitted for monitoring of clinically healthy animals (i.e. no clinical signs of sheep scab).
Quarantine	Samples are submitted for testing of bought-in or returning animals (i.e. animals in quarantine).
Retest	Samples are submitted for retesting of flocks which had a previous positive diagnosis.
Wool loss	Samples are submitted for animals displaying signs of wool loss, but not itchy.
Other	Samples are submitted for reasons which did not fit into the previous categories. A free text option was available to specify the reason.

3.2.2.3. Risk factor analysis

To establish whether specific factors had a significant relationship to the calculated serostatus, six fields from the submission form database were chosen for analysis: double fencing, common grazing, contract shearing, contract dipping, shared gathering facilities, and shared livestock trailers. These factors were selected as the data had a completion rate which exceeded 50%, and they have previously been identified to, or are commonly thought to, influence the risk of sheep scab outbreaks (ADAS, 2008). All fields selected had a binary outcome (i.e. 'yes' the variable applied to the holding, or 'no' the variable did not apply to the holding). Therefore, a multivariable logistic regression was applied to the six fields to test for association to the calculated serostatus.

In addition, as having a past sheep scab outbreak on a holding has been shown to significantly increase the chance of further outbreaks (Rose and Wall, 2012a), separate univariate logistic regressions were performed using the fields 'sheep scab previously diagnosed' and 'sheep scab previously suspected' (both within the past two years) to test the association with the calculated serostatus. As before, these fields had a binary outcome (i.e. 'yes' or 'no').

3.2.2.4. Comparison to existing scanning surveillance

To evaluate the potential use of the sheep scab ELISA data for scanning surveillance, the sheep scab ELISA submissions with a positive serostatus were compared to the count of VIDA positive scrapes. The VIDA positive scrapes (as previously described in 2.2.1) were a subset from the whole database matching the study period of the sheep scab ELISA, with both datasets aggregated by month to facilitate a descriptive temporal analysis. To compare the spatial distribution of these two datasets, the VIDA positive scrapes visualised by the regional geolocator previously described in 2.2.2.1 were overlaid by the sheep scab ELISA submissions with a positive serostatus.

3.3. Results

3.3.1. Calculated serostatus

A total of 542 submissions were received and tested between the 1st February 2017 and 31st August 2019. Of the 542 submissions, 333 (comprising of 2,375 blood samples) had sufficient submission data for inclusion in the analysis. As two submissions, comprising of 24 samples, were performed at the MRI using different reagents, these were excluded from all analyses using serostatus, leaving 331 submissions, comprising of 2,351 blood samples.

Using the OD cut-off values as described in Table 3.1, 82.7% (n = 1,945) of the 2,351 blood samples had an OD result classified as negative, 13.8% (n = 324) as positive, and 3.5% (n = 82) as suspect. Then, using the new framework to present a serostatus for each of the 331 submissions (each containing between 1 and 53 individual samples) 43.2% (n = 143) submissions were classified as positive, and 56.8% (n = 188) as negative.

3.3.2. Descriptive analysis

As shown in Figure 3.1, a substantial increase in monthly submissions occurred across the study period. There were no submissions (n = 0) for the months of April, May and July 2017. The maximum number of submissions occurred in the last month of the study period, August 2019 (n = 38). Some seasonal variation was observed, with higher numbers of submissions being made in autumn and winter. This was particularly evident across early 2019 when the highest number of submissions occurred in February (n = 33), and the lowest in June (n = 6).

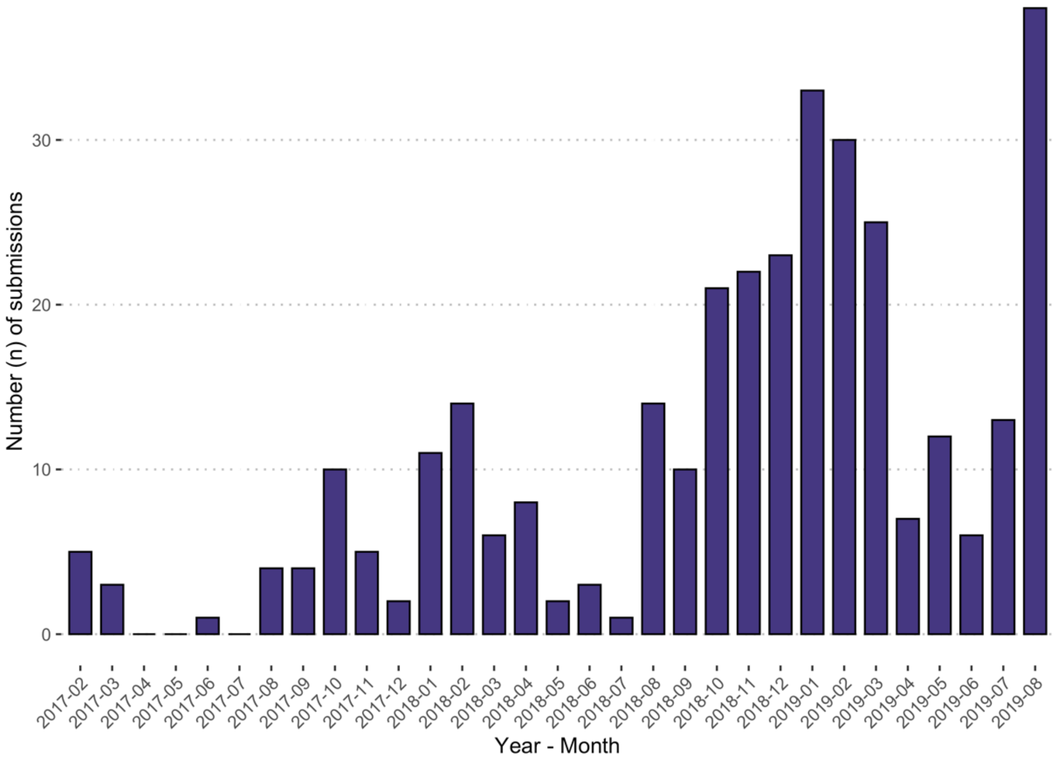


Figure 3.1: *Monthly trend of sheep scab ELISA submissions (n = 333), from February 2017 - August 2019 inclusive.*

The largest percentage of submissions (30.6%, n = 102) contained the recommended 12-samples, as displayed in Figure 3.2. Single sample submissions were the next most frequent, representing 24.0% (n = 80) of the total submissions. Submissions which included between 1 and 11 samples represented 63.1% (n = 210) of the total, while 6.3% (n = 21) contained more than 12 samples.

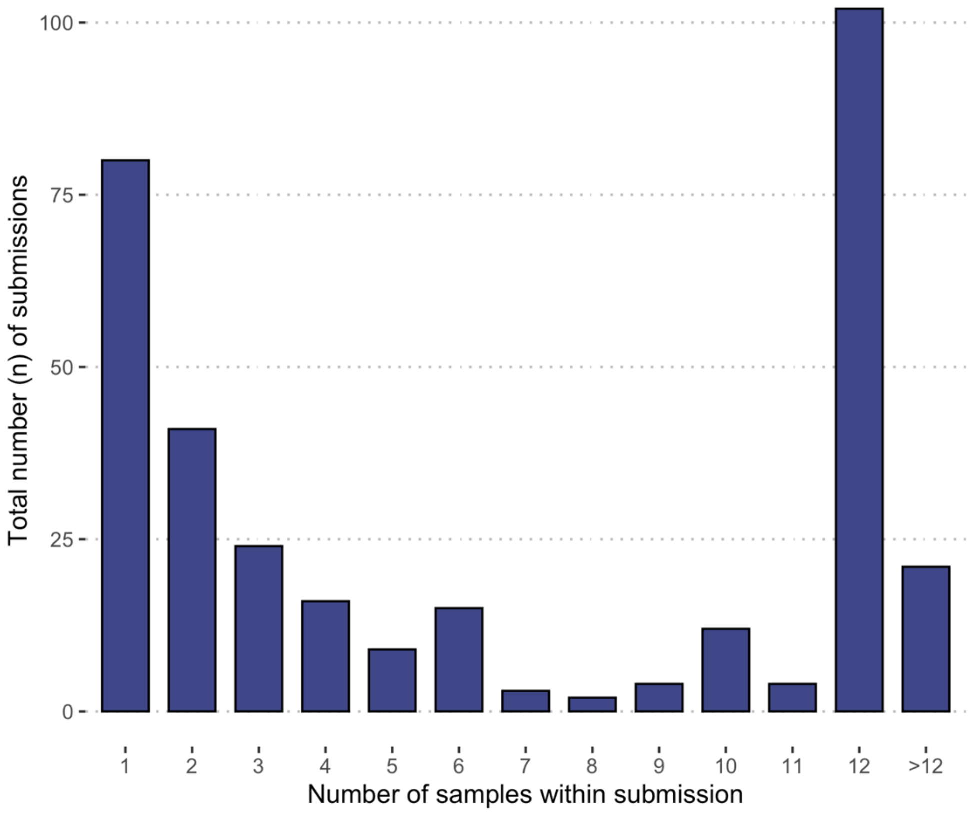


Figure 3.2: *Number of samples contained within a submission, as a percentage of total submissions (n = 333).*

In total, 289 of the 331 sheep scab ELISA submissions included a geolocator which allowed spatial coordinates to be obtained for plotting. Of these submissions, 67.7% (n = 195) originated from England, 27.1% (n = 79) from Wales, 4.8% (n = 14) from Scotland and 0.3% (n = 1) submission from Northern Ireland (Figure 3.3). Submissions derived from 30 of the total 41 NUTS level 2 regions in the UK. There were no submissions (n = 0) made in 11 regions, 10 of which were in England and one in Scotland. There was no significant difference between the number of positive and negative serostatus in regions where submissions were made ($p > 0.05$ using a chi-squared test).

In England, submissions predominately derived from the west and south of the country (Figure 3.3). The highest number of submissions in England were from: Cumbria (n = 40); Shropshire and Staffordshire (n = 25); Derbyshire and Nottinghamshire (n = 19); Northumberland and Tyne and Wear (n = 19) and East Anglia (n = 14). In Wales, the majority (n = 50) of the submissions originated from one region, West Wales and The Valleys. This was the highest number in a single region across all countries. Scotland had a much lower number of submissions, with the highest number from Eastern Scotland (n = 7), followed by the Highlands and Islands (n = 5).

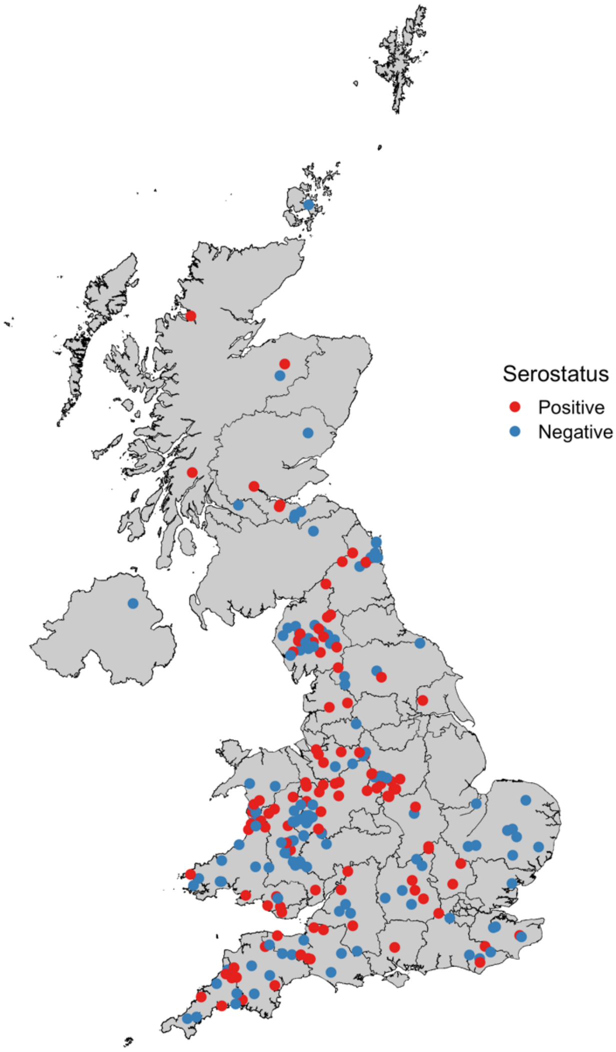


Figure 3.3: *Spatial distribution of the sheep scab ELISA submissions from February 2017 to August 2019 inclusive (n = 289). Colour of the point indicates the calculated submission serostatus: red = positive, blue = negative.*

The percentage of data completeness for all fields captured from the submission form is shown in Figure 3.4. Of the 35 fields, 48.6% (n = 17) had over 50% completion. The median percentage of completion across the fields was 44.1%. The variables from page 1 of the submission form (Appendix 4A) had an average completion of 53.2%, which was significantly different to the completion of the variables on page 2 (Appendix 4B), of 20.1% ($p < 0.001$).

Field	Completeness
Veterinary Practice	98.5%
Reason for Submission	78.4%
Type of Flock	68.8%
Holding Number	66.1%
Was an OP dip within last 12 months? Y/N	65.8%
Is common grazing used? Y/N	64.9%
Is double fencing used? Y/N	61.6%
Was an OP shower used within last 12 months?	61.0%
Was an injectible ML used within last 12 months?	60.7%
Are contract shearers used? Y/N	58.9%
Are shared gathering facilities used? Y/N	58.3%
Are shared trailers used? Y/N	58.3%
Has scab been suspected within the last 2 years? Y/N	58.3%
Are contract dippers used? Y/N	58.0%
Has scab been diagnosed within the last 2 years? Y/N	57.4%
Number of breeding ewes	55.6%
Purchase - Treatment? Y/N	45.3%
Last date of acaraide treatment	44.1%
Postcode of holding	42.3%
Last acaracide product used	42.0%
Other comments/risk factors	33.6%
Month of injectable ML use within last 12 months	27.6%
Quarantine period after purchase	26.1%
Tack - Treatment? Y/N	24.3%
Mart - Treatment? Y/N	20.7%
Purchase - Treatment Product	12.3%
Shows - Treatment? Y/N	12.3%
Quarantine period retuning from tack	12.0%
Month of OP dip use within last 12 months	11.7%
Quarantine period upon retuning from the mart	5.4%
Tack - Treatment Product	3.6%
Quarantine period returning from shows	3.6%
Month of OP shower use within last 12 months	1.5%
Mart - Treatment Product	0.0%
Shows - Treatment Product	0.0%

Figure 3.4: *Percentage completeness for all fields captured from the sheep scab ELISA submission forms (n = 333).*

Of the 261 (78.4%) submissions which indicated the reason for testing, 'itchy' was the most frequent reason for submission, representing 56.7% (n = 148) of the total submissions. The second most frequent reason was for 'monitoring', 32.6% (n = 85) of submissions. The other reasons for testing cumulatively represented 10.7% (n = 28) of submissions as shown in Table 3.3. In addition, of the 56 submissions which only contained one sample, 87.5% (n = 49) were submitted due to 'itchy' sheep, with the remaining 12.5% (n = 7) submitted for either quarantine, retests, wool loss or 'other' reasons. No submissions (n = 0) containing only one sample were submitted for monitoring. In contrast, of the 82 submissions containing 12 samples, 65.9% (n = 54) were submitted for monitoring, 29.3% (n = 24) were submitted for the diagnosis of 'itchy' sheep, and the remaining 4.8% (n = 4) for quarantine, retests and 'other' reasons.

Table 3.3: *Reasons submissions were made for the sheep scab ELISA test (n = 261).*

Reason	Number of submissions	Percentage (%)
Itchy	148	56.7%
Monitoring	85	32.6%
Quarantine	11	4.2%
Retest	11	4.2%
Wool loss	2	0.8%
Other	4	1.5%

The 'farm type' was indicated for 229 submissions. Almost half of submissions originated from 'lowland' flocks (48.9%, n = 112). The count of submissions received from both 'upland' and 'hill' flocks were similar (Table 3.4), with only a small percentage (4.8%, n = 11), originating from 'mixed' flocks.

Table 3.4: *Primary farm type of submitting holdings (n = 229).*

Farm Type	Number of submissions	Percentage (%)
Hill	54	23.6%
Upland	52	22.7%
Lowland	112	48.9%
Mixed	11	4.8%

The relationship between 'reason for testing' and 'farm type' is shown in Figure 3.5. Submissions from lowland flocks were mostly from itchy sheep, representing 75.5% (n = 80) of the total lowland submissions. This proportion decreased to 52.1% (n = 25) for upland flocks and 34.0% (n = 17) for hill flocks. For mixed farm types, submissions from itchy sheep represented only 27.3% (n = 3) of total submissions. Conversely, lowland farms had the lowest proportion of submissions for monitoring, at 14.2% (n = 15), while upland and hill farms represented 43.8% (n = 21) and 60.0% (n = 30) respectively. Mixed land types had the highest percentage of submissions submitted for monitoring, 72.7% (n = 8).

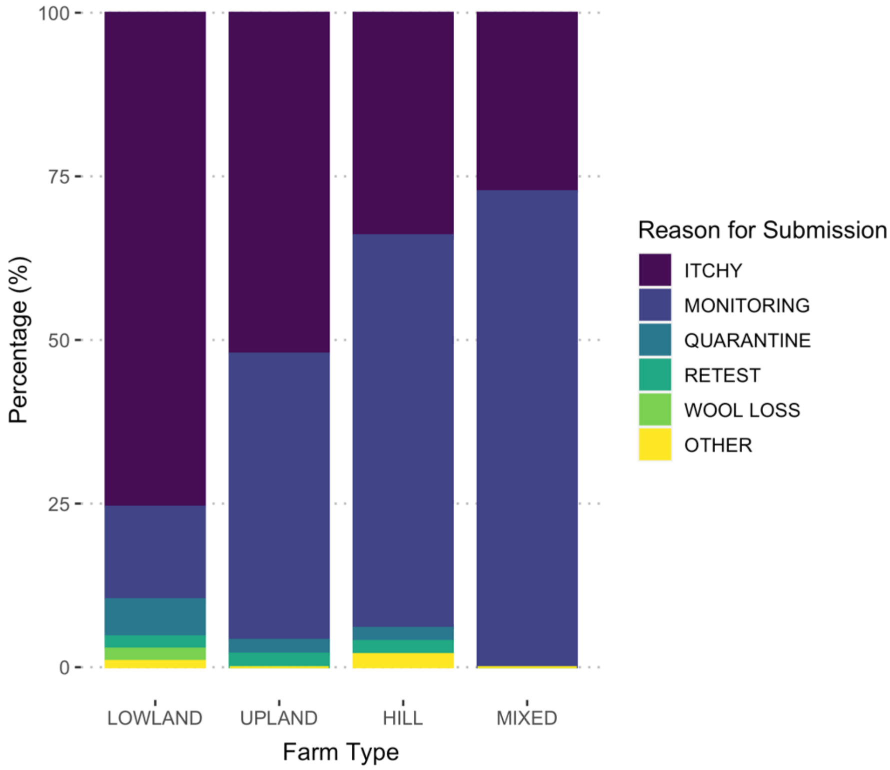


Figure 3.5*: Distribution of the reasons for testing, grouped by the flock's farm type. Each bar represents the proportion of reasons for testing, for the submitting farm type: lowland (n = 106), upland (n = 48), hill (n = 50) and mixed (n = 11).*

3.3.3. Risk factor analysis

Six fields as previously described in 3.2.2.3 were assessed as potential risk factors of sheep scab. During model selection, three of the fields ('contract shearers', 'shared gathering facilities' and 'shared livestock trailers') were removed from the analysis as there was no evidence that these factors, which were orthogonal to the remaining ones, had a clear influence on the dependent variable of interest, with p-values exceeding 0.6. A significant negative relationship was observed between 'double fencing' and positive serostatus (Table 3.5). A marginally significant positive correlation was shown between 'contract dipping' and positive serostatus, while 'common grazing' did not have any association to the calculated serostatus.

Table 3.5: *Output of the logistic regression model. AIC = 225.21. '.' indicates a marginally significant p-value between 0.05 and 0.1. '*' indicates a significant p-value between 0.01 and 0.05. n = 170 sheep scab ELISA submissions used in estimation.*

Coefficient	Estimate	Std. Error	z-value	p-value
Intercept	-0.2654	0.1254	-2.116	0.0344 *
Common grazing	0.2590	0.2633	0.984	0.3253
Double fencing	-0.5291	0.2519	-2.100	0.0357 *
Contract dipping	0.5773	0.3009	1.918	0.0551 .

There was no significant association between 'sheep scab previously diagnosed' and positive serostatus ($p > 0.05$). However, a significant positive association was observed between 'sheep scab previously suspected' and positive serostatus ($p < 0.01$).

3.3.4. Comparison to existing scanning surveillance

From February 2017 to August 2019, 268 VIDA positive scrapes and 143 sheep scab ELISA positive serostatus were diagnosed. The monthly count of positive serostatus compared to VIDA positive scrapes is shown in Figure 3.6. With the exception of a large peak in VIDA positive scrapes from December 2017 to April 2019, reaching a maximum of 44 positive scrapes in February 2018, the pattern and count of the VIDA positive scrapes was very similar to the number of sheep scab ELISA positive serostatus.

Of the total submissions, 260 (97.0%) VIDA positive scrapes and 128 (89.5%) sheep scab ELISA positive serostatus included a geolocator. The sheep scab ELISA positive serostatus were then overlaid on the VIDA positive scrapes as shown in Figure 3.7. The highest number of VIDA positive scrapes across the study period originated from Wales, which represented 63.8% (n = 166) of the total positive scrapes. Scotland then represented 20.8% (n = 54) positive scrapes, while England had the lowest proportion observed, at 15.4% (n = 40) of the total positive scrapes. In contrast, 70.3% (n = 90) of the sheep scab ELISA positive serostatus were from England. Of the remaining positive serostatus, 25.0% (n = 32) originated from Wales, and 4.7% (n = 6) from Scotland.

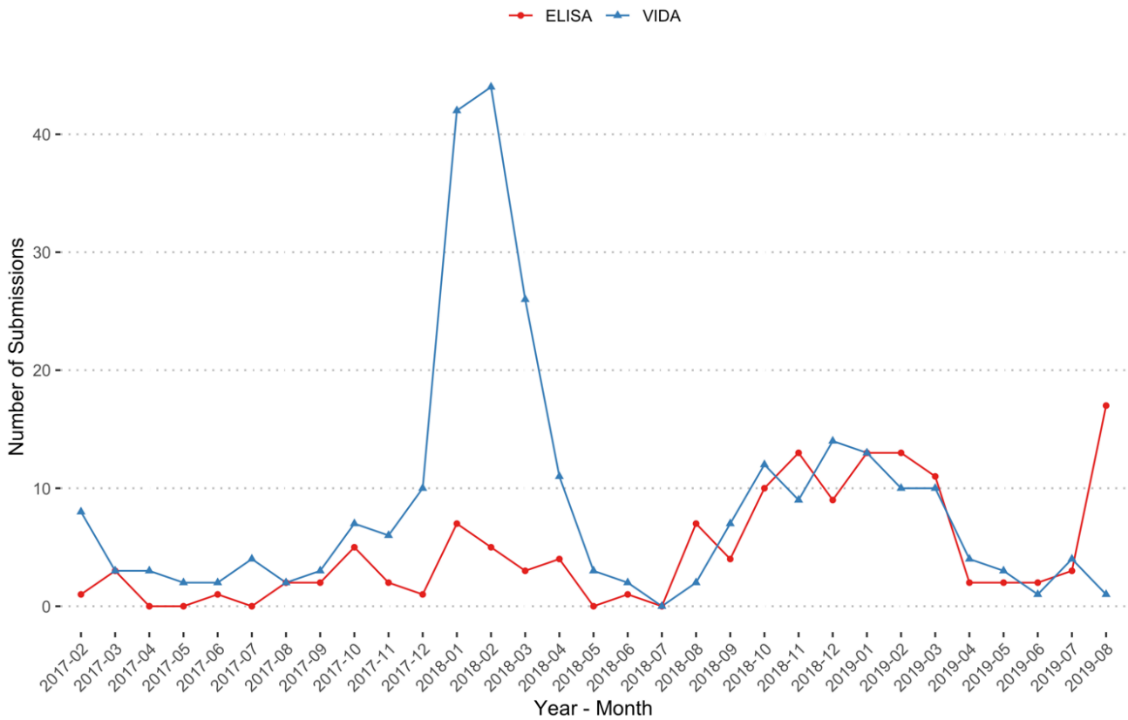


Figure 3.6: *Monthly trend of the total VIDA positive scrapes (n = 268) and sheep scab ELISA positive serostatus (n = 143), from February 2017 to August 2019 inclusive. Red line = sheep scab ELISA positive serostatus, blue line = VIDA positive scrapes.*

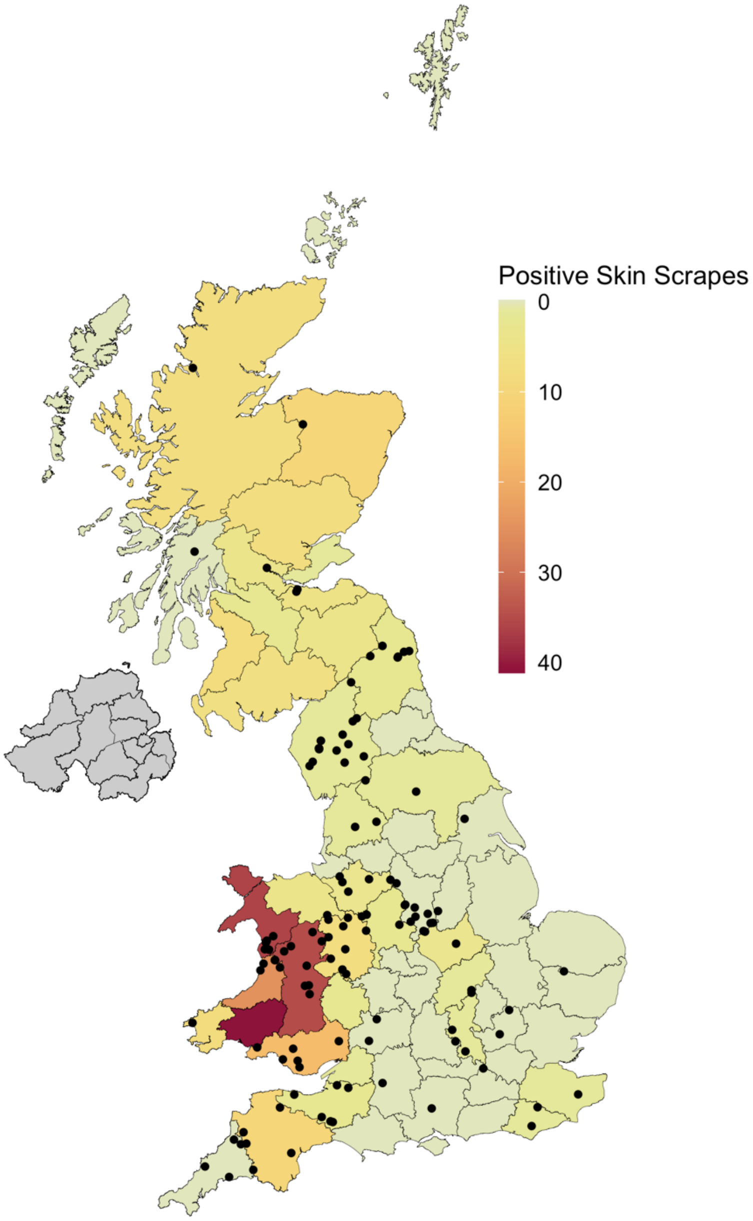


Figure 3.7: *Spatial distribution of the VIDA positive scrapes (n = 260) represented by the shaded regions, overlaid by points of the locations of the sheep scab ELISA positive serostatus (n = 128).*

3.4. Discussion

In this chapter, data from a new diagnostic sheep scab ELISA were collated and analysed for the first time to create a new data source for the scanning surveillance of sheep scab. These data were also utilised to provide information on its use and uptake since commercialisation and to investigate the risk of sheep scab associated with particular management factors. As would be expected of a new diagnostic test, the number of submissions increased significantly across the study period. Seasonal fluctuations in the submission rate were also present, with the highest number of submissions occurring in the autumn and winter months. This seasonal pattern is well established for sheep scab, thought to be caused by particular climatic and management factors (French et al., 1999). Although, here, increased submissions across autumn and winter may have also been influenced by having easier access to sheep for blood sampling in winter due to housing or gathering for other seasonal management tasks. The sheep scab ELISA is still a relatively new option for the diagnosis of sheep scab in comparison to the existing skin scraping methodology, hence awareness of the test is still being established. The highest number of submissions, received in the last month of the study period, is an encouraging result for the further uptake of this new diagnostic test to reaching its full potential in the near future.

As 12-sample submissions are recommended to achieve an accurate estimation of a flock's serostatus, it is promising that these were the most frequently recorded. In addition, 66% of the 12-sample submissions were made for monitoring purposes, while no single submissions were made for monitoring purposes. It is likely this is a result of effective knowledge transfer campaigns undertaken by Biobest and MRI to promote the test and to provide guidance on its use. As well as through education, the compliance may have been further encouraged by offering discounted testing when 12 samples were presented. Currently it costs £6.00 per sample for 12-sample submissions (to a total of £72.00 for a 12-sample submission) as opposed to £9.00 for an individual sample submission, or £8.50 per sample for submissions with between 2 and 11 samples (Biobest, 2020). While the majority of submissions included 12 samples, a large proportion included only one sample. As submissions with one sample were predominantly (87.5%) made to test itchy sheep (i.e. sheep with clinical signs), the use of a skin scrape test could have potentially offered a faster diagnosis in these cases. However, submission of a skin scraping sample to the APHA for testing (in England and Wales) costs significantly more than the blood sample at £24.70 per ectoparasite screen (APHA, 2020b). In addition, if lesions are not well-established on the sheep, skin scrapings can be difficult to perform and thus taking a blood sample would offer a much more convenient and reliable alternative. For submissions containing between 2 and 11 samples, a possible explanation would have been not having enough sheep within the management group or not enough presented by the farmer for blood sampling, for example when testing quarantined animals, or to test a targeted group of animals with clinical signs. Hence, these results suggest a good overall understanding of the recommendation and purpose of the sheep scab ELISA from the submitting holdings.

The sheep scab ELISA submissions were mostly concentrated in high prevalence areas such as Wales, North England and South West England (French et al., 1999; Rose et al., 2009). This pattern of uptake may have been influenced by an increased awareness of sheep scab in these areas, which is likely to have motivated holdings to develop a proactive monitoring strategy and ease the potential economic burden from outbreaks. This supports work which predicted that the sheep scab ELISA would be adopted in high-risk scenarios (Mohr et al., 2020). In contrast, despite Biobest being based in Scotland and having shown a high number of VIDA positive scrapes diagnosed from Scotland over the same period, the number of submissions originating from Scotland was particularly low. It is possible that the uptake in Scotland over this time period was significantly affected by the free testing (through skin scrapings). Thus, under these circumstances, it would be uneconomic to use this test when there is a free option available. Another important factor to consider is the notifiable status of sheep scab in Scotland (see 2.3.4). As control was the primary reason for its introduction (*Veterinary Record*, 2010), in future it may be possible to incorporate the sheep scab ELISA into Scotland's surveillance strategy towards decreasing the prevalence of sheep scab and minimise the pressure on acaricidal treatments. However, this could present some challenging situations. As the sheep scab ELISA has been advocated for monitoring purposes, submissions could be part of a responsible proactive management strategy. If those submissions were to test positive, movement restrictions would be applied to the relevant flock(s) (The Scottish Government, 2010), meaning the use of the test could disadvantage farmers who are taking a proactive approach. Furthermore, as the sheep scab ELISA cannot differentiate between an active sheep scab outbreak and a successfully resolved outbreak (Hamer et al., 2019), there may be a possibility of false positive results, with potential implications on restriction of movements for the flock. As such, careful consideration over how to encourage a wider adoption of the sheep scab ELISA in Scotland must be taken so not to impair the income or willingness of responsible farmers.

An important component of any serodiagnostic test is its interpretation, as OD provides a quantitative result for a single sample, but ultimately the veterinarian and farmer are interested in a qualitative (yes or no) answer for the whole flock. Interpretation of the results at the flock level is currently undertaken by an experienced Biobest veterinarian, combining the OD results for the submission with the information provided on the submission forms. However, this is considerably time consuming and subjective, thus prone to human error. The new framework for the interpretation of the OD results applied a singular value of prior risk, 10%, to echo the current estimated national prevalence of sheep scab (Bisdorff et al., 2006) and calculate the overall submission serostatus from the individual OD results. This produces an automatic outcome of positive or negative, which could provide a more standardised approach and be used to cut the time required for interpretation. Furthermore, this could become fully automated which would increase the timeliness of results delivery to farmers and decrease costs for Biobest. However, in practice, the risk of sheep scab is very individual and thus much more difficult to quantify. As shown using the existing scanning surveillance data in Chapter 2, and in previous studies using farm-level survey data (French et al., 1999; Rose et al., 2009), there is a high variability in risk dependent on geographical location. Likewise, the risk of sheep scab transmission varies between holdings dependent on their individual management practices (Rose and Wall, 2012; Vineer, 2011). A single prior value was utilised to create a framework to classify submission serostatus that was simple to implement across all submissions. However, as demonstrated by the analysis, prevalence was appreciably different across the three countries. Therefore, future work to refine with this framework could be aimed at including the regional variation of risk, utilising previous survey work (Rose et al., 2009) and/or consider using the management data included on the submission form to tailor the calculated submission serostatus to each submission's risk profile.

A further objective of this chapter was to explore the ability of this data to determine potential risk factors associated with sheep scab infestations, which could also inform the risk factors utilised when calculating the submission serostatus. Unexpectedly, this study showed the use of common grazing, a well-accepted and proven risk factor for increasing the likelihood of sheep scab outbreaks (Cross et al., 2010; Rose and Wall, 2012), was not a significant predictor of the submission's serostatus. Hill holdings, which more frequently have access to common grazing, made submissions for monitoring in 60% of cases. In this instance, the lack of an association may suggest these holdings, which are taking a proactive approach to their sheep scab management by monitoring, have reduced outbreaks. In contrast, lowland holdings predominantly (76%) submitted due to suspected cases. Therefore, lowland submissions, where common grazing is unlikely, may have had a higher rate of positive serostatus submissions which could have influenced the model's accuracy.

Furthermore, the use of contract dipping was shown to have a marginal effect on increasing the likelihood of sheep scab infestations. While the introduction of persons and equipment onto a premise does present some risk to the holding, contract dipping is used as a treatment for sheep scab. Thus, contract dipping is only undertaken if ectoparasitic diseases such as sheep scab or lice have previously been suspected, or as part of prophylactic measures. As holdings which had previously suspected sheep scab were significantly more likely to have a positive serostatus submission, the past use of contract dipping to control sheep scab may account for its effect here. However, it is also likely that a number of further biases relating to the submitting population due to the voluntary nature of these diagnostic submissions may also influenced the ability of this model to predict the risk factors associated with a positive submission.

Double fencing is recommended as a good biosecurity practice to decrease the likelihood of direct transmission for many infectious diseases, such as bovine tuberculosis (O'Hagan et al., 2016). As such, the use of double fencing is commonly recommended to decrease the risk of sheep scab (Sustainable Control of Parasites in Sheep [SCOPS], 2020). Here, the use of double fencing showed a significant negative association to a positive submission, indicating that the use of double fencing is associated with a reduced likelihood of sheep scab.

In addition to investigating the current use of the sheep scab ELISA, a further objective was to assess the potential added value of the sheep scab ELISA data as an additional source of scanning surveillance. Despite its relatively recent commercialisation, the uptake was similar to the skin scrape test as the temporal pattern and total number of positive serostatus submissions was very similar to the number of VIDA positive scrapes with the exception of a spike in VIDA positive scrapes from December 2017 to April 2018. This spike was likely caused by the APHA free testing initiative as previously discussed in Chapter 2 (Figure 2.7). As the trend in positive serostatus submissions is very similar to the current well-established database despite their different diagnostic methods, this could support the use of the sheep scab ELISA to complement the current surveillance for sheep scab in GB. Yet, spatially the positive serostatus submissions captured a slightly different demographic, with a much higher proportion of positive serostatus submissions originating from England in comparison to the VIDA positive scrapes (70% vs 15% respectively). The high number of positive serostatus submissions in these areas may be a result of the sheep scab ELISA detecting subclinical cases, where a skin scraping may not have been an appropriate option. As a result, the sheep scab ELISA would capture a different cohort, which would support its future use as complementary source of scanning surveillance for sheep scab. Furthermore, as the sheep scab ELISA is recommended for monitoring purposes, the sheep scab ELISA offers an easily extractable denominator ('overall submissions') which could provide an estimation of the prevalence of sheep scab across the UK.

The proportion of submissions with a positive serostatus (43%) was higher than previous estimates from scanning surveillance and survey data (ranging from 9% to 36%) (Bisdorff et al., 2006; Cross et al., 2010; Rose et al., 2009), whilst the number of positive individual blood samples (14%), as categorised by their OD results, aligned more closely with current prevalence estimates (Bisdorff et al., 2006; Rose et al., 2009). In the case of sheep scab, even if a minority of animals within a flock are positive the whole flock status is interpreted as positive. This emphasises the intrinsic differences between the picture of sheep scab presented through the skin scraping method, used in the VIDA database, and sheep scab ELISA. The sheep scab ELISA adopts a flock level approach by taking multiple samples for monitoring, which means it is able to provide a powerful estimation of the flock level serostatus, even under low level infestation and subclinical disease (Hamer et al., 2019). A negative submission can therefore also be a reliable indicator of the absence of infestation at that time point. In contrast, the VIDA detects mites from skin scrapes at an individual animal level, which are only conducted when clinical signs are obvious. In addition, the result of the skin scrape test is also reliant on the initial quality of the scrape. As a consequence, false negatives results are more likely to occur. Thus, the data originating from the sheep scab ELISA, while sharing some of the limitations of the VIDA database (i.e. voluntary submissions), also presents some considerable benefits, like the high sensitivity of the test and the flock level diagnosis.

A major part of this study, which enabled all of the above analyses, was the collation of the data to provide a new usable source of data for scanning surveillance. The created data source includes all sample results and all information from usable submission forms, which presents an unprecedented opportunity for more extensive analysis and a very valuable tool for evidence-based recommendations for future control strategies. However, as is often the case with data which was not intended for these purposes, the work required for the collation and formatting was significant and may provide a substantial barrier to their future use (VanderWaal et al., 2017). As the submission forms were hand-written and the location of certain elements were not consistent (e.g. location of the 6-digit submission number on the submission form), no software could be applied for their automatic digitisation. It was estimated that digitisation of all 542 submissions consisting of 3,089 blood samples (from

15 months of records) took in excess of 130 hours. This was approximately divided into: 20 hours digitising the result report, 60 hours digitising the submission forms and a further 50 hours on data cleaning to convert the data into a useable format for analysis. Therefore, continued analysis of these data as part of a more formal surveillance system would require substantial changes to their collection and storage to decrease the time and labour required. Ideally, a fully integrated digital system for data collection, such as is used for electronic patient records in human healthcare settings (Terry et al., 2019), could be adopted to increase the accessibility of the data. This would require the farmers to complete the submission form online using a computer, tablet or smartphone which would link to the unique 6-digit submission number used in the laboratory for the results. The information entered would then auto-populate a database, largely mitigating the time required for data cleaning whilst allowing the results to be integrated easily. In addition, the use of mandatory fields within the digital submission forms would likely increase the overall completion from the current median of 44% and thus increase the value of the collected data for scanning surveillance purposes. This would be particularly beneficial for the variables on the second page which were more often incomplete. However, changing the systems to become fully digital would require a complete overhaul of the current workflow and may not provide sufficient commercial value. In addition, it is also possible that requiring farmers and veterinarians to complete this information may discourage the use of thee sheep scab ELISA and thus hinder its uptake. Alternatively, and perhaps more feasibly, smaller changes to current practices could offer a more practical interim solution. These could include altering the submission forms to reduce ambiguity, such as providing tick boxes and an escape option to the fields which currently require circling. Also, it may be possible to implement an optical character recognition software to automatically extract the hand written information (Ridge, 2015) to limit time spent on data interpretation and extraction, thus reducing the costs of labour. Furthermore, the submission forms could be optimised to reduce the number of fields that are essential for the interpretation of the form in relation to the risk profile of the holding.

In conclusion, this part of the research showed a steady uptake in the use of the sheep scab ELISA since the beginning of testing with an established seasonal pattern and broad uptake among England and Wales, but with few submissions originating from Scotland. The recommended 12-sample submissions for monitoring were the most frequently submitted, showing a good awareness of this test's application. As the majority of submissions were made from itchy sheep, this test is also widely used to diagnose sheep scab in sheep with clinical or subclinical signs. This study also showed a negative association between double fencing and a positive scab serostatus; however, common grazing was not identified as a risk factor. Furthermore, the positive serostatus submissions showed a very similar temporal pattern to the existing scanning surveillance (VIDA positive scrapes). Finally, this study created a new database using data from the recently commercialised sheep scab ELISA which could be further utilised as an evidence-base towards improving approaches to the control of sheep scab.

4. General discussion

Endemic diseases are, unfortunately, a very familiar problem in modern livestock farming, with their effect felt throughout the industry. However, with an ever-increasing pool of available data as farming moves into the digital age (VanderWaal et al., 2017), the enhanced use of these data may present new opportunities to develop a valuable, cost-effective and evidence-based platform to inform the future management of endemic diseases (Bennett and IJpelaar, 2005; Gates et al., 2015). Using sheep scab as a model, this research project aimed to provide an example of this potential. By using existing surveillance data and evaluating a new data source, our knowledge and understanding of this endemic disease has been enhanced, specifically towards improving control strategies for sheep scab.

At present, improving the use of existing scanning surveillance data may present the most accessible route to improving the management of endemic diseases. The VIDA database, as described in Chapter 2, currently provides scanning surveillance for many diseases across GB. Like most established databases, it is presented in a standardised format which decreases the time required for data cleaning, facilitating easier analysis. Therefore, exploiting these data further could provide a cost-efficient approach to improving current surveillance outputs. As demonstrated through the application of the TADA analysis in Chapter 2, there is significant potential to use this source to fulfil more specific objectives, such as the evaluation of past disease control initiatives. Dependent on the specific disease, exploiting existing data sources further might provide sufficient information and contribute towards the final objective of improving the control of an endemic disease, whether this is to decrease the prevalence or eradication. If the existing source, however, is not sufficient on its own, new data sources should be explored and taken advantage of.

Accessing and utilising new data sources is usually more challenging, but could have the potential to add significant value to the existing scanning surveillance. As demonstrated in Chapter 3, the work required to create valuable information from a new data source was considerably time-consuming (Barrett, 2017; McCue and McCoy, 2017; Schneeweiss, 2014), however can be very rewarding. Crucially, the work undertaken to produce the new data source in Chapter 3 resulted in the creation of an extensive database which has provided further knowledge to inform some crucial aspects of sheep scab management. For other diseases, when selecting possible sources of new data, it is likely there will be a high variability in the pre-processing work required, dependent on the current data management practices employed (Sun et al., 2018). Thus, if multiple sources are available, it may be possible to select sources which require the least pre-processing, or those where technology could be employed to streamline the pre-processing. Despite the inevitable initial outlay required to create these data sources, it is quite possible that if the source is selected carefully, these costs would be recovered if the control strategies of these diseases were to be improved as a direct result of their analysis. Therefore, data sources should not be dismissed purely on their degree of accessibility, as their benefit could outweigh the initial costs. Instead, a balance needs to be achieved to estimate the value of these sources, with potential incentives from government or public funding to promote good data management and sharing of data.

For sheep scab, there is currently a high degree of motivation throughout the industry to reduce the prevalence of this disease, particularly in "hotspot" areas. To create a cost-effective evidence-base to inform these control strategies, improving the use of available data is considered a priority by stakeholders. The new database produced in this research project was collated through collaboration with Biobest as part of a wider project driven by the emergence of antiparasitic resistance. This multi-disciplinary project funded by the VMD (DEFRA – VMD Lot 2 Antiparasitic Resistance: Sheep Scab) aims to guide the development of targeted and coordinated activities across the industry. Beyond this project, other management strategies have been, and are currently being developed by government and industry. These include the Sheep Scab (Scotland) Order 2010 which was introduced as a result of industry pressure (Animal Health and Welfare Wales, 2018; The Scottish Government, 2010), and a recently announced £5 million funding package from the Welsh Government, to aid eradication of sheep scab in Wales (Vet Times, 2019), a major hotspot for outbreaks. Furthermore, in January 2020, a meeting was hosted by the University of Bristol which assembled a group of stakeholders including farmers, veterinarians, government, industry and researchers to consider options for future sheep scab management in GB.

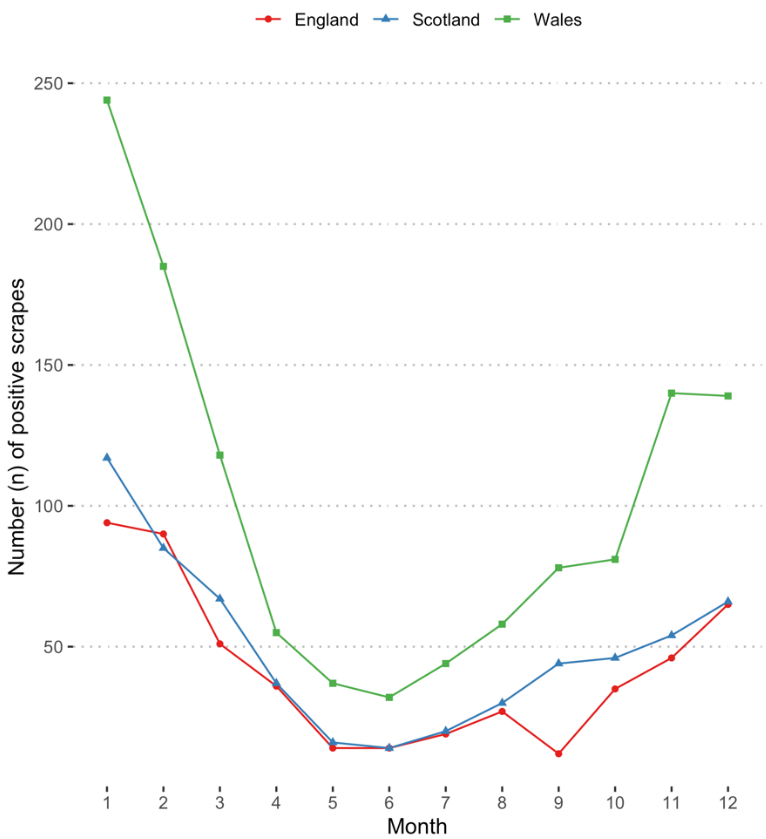
To date, the approach towards achieving sheep scab control has been driven by targeted initiatives organised and funded by government and industry bodies, as outlined in Chapter 2. It is likely that in absence of a national eradication scheme, targeted initiatives will continue to be the primary tool towards control. The evidence presented in this project could, however, guide their evaluation and implementation in a cost-effective manner. The use of free skin scraping testing, for example, would capture the attention of farmers in the short term, with the aim to increase submission from suspected cases. If the sheep scab ELISA was included when offering free testing, this would also allow capture of subclinical cases, which are important reservoirs of mites (Hamer et al., 2019), and may encourage farmers to adopt a more proactive strategy through regular monitoring of their flocks. If sheep scab was diagnosed, support should be provided to ensure the correct treatment is applied, to decrease the selection pressure on acaricidal drugs resulting from incorrect use. This also raises the importance of education, through knowledge transfer or knowledge exchange campaigns (Farm Animal Welfare Committee, 2011), to emphasise the importance of good biosecurity measures, such as double fencing, as shown in Chapter 3. Practically, all these initiatives are expensive and labour intensive. Initially, however, efforts could be targeted in hotspot regions such as Wales, as identified in Chapter 2. As it has been previously shown, targeted approaches for sheep scab control are more effective, as they encourage a collaborative approach amongst neighbours (Sargison et al., 2006). This was also demonstrated on a smaller scale, by using the sheep scab ELISA to test seven flocks of Herdwick sheep sharing a common grazing, a targeted project coordinated by a local veterinarian (APHA, 2019; *A Carson, personal communication*). In this case, the sheep scab ELISA detected subclinical disease in five of the holdings, highlighting the importance of the early detection of subclinical disease, and encouraging local cooperation between holdings.

Compliance is also a particular issue for sheep scab, as control is very reliant on strategies adopted by neighbours (Nixon et al., 2017). Additionally, sheep scab has been stigmatised as a disease related to poor management and is therefore not as openly discussed as other endemic diseases (Cross et al., 2010). For that reason, action plans could be more consumer-led, providing economic reward for responsible farmers. This could be achieved through the deployment of an accreditation scheme similar to the Enzootic Abortion of Ewes (EAE) accreditation scheme in Scotland (SRUC, 2020), which rewards members of these schemes with higher prices paid at markets. Regardless of the strategies selected, the control of sheep scab will not be achieved in the short term, therefore commitment and sustainability are of paramount importance.

In conclusion, this research has achieved the aim to enhance the use of existing and new data sources for the scanning surveillance of sheep scab, specifically to guide future control strategies. It has exploited an existing scanning surveillance data source, the VIDA database, to identify disease "hotspots" in Wales, which could be the focus for more targeted disease control efforts. It has also shown other potential outcomes from the existing data, through the use of a TADA to show that free testing had the largest impact on positive scrapes. In addition, it has provided information on the current use and uptake of the sheep scab ELISA, demonstrating a good awareness of this test's application for monitoring, while also being widely adopted to diagnose sheep with clinical signs. Furthermore, this new data source showed the presence of double fencing is significantly associated with a decreased the risk of infestation. Lastly, this project resulted in the creation of a new data source that could be used to complement the existing surveillance data of sheep scab. Ultimately, the framework used here could be applied to other endemic diseases.

Appendices

Appendix 1: Monthly aggregate of positive scrapes from 2003-2018 by country

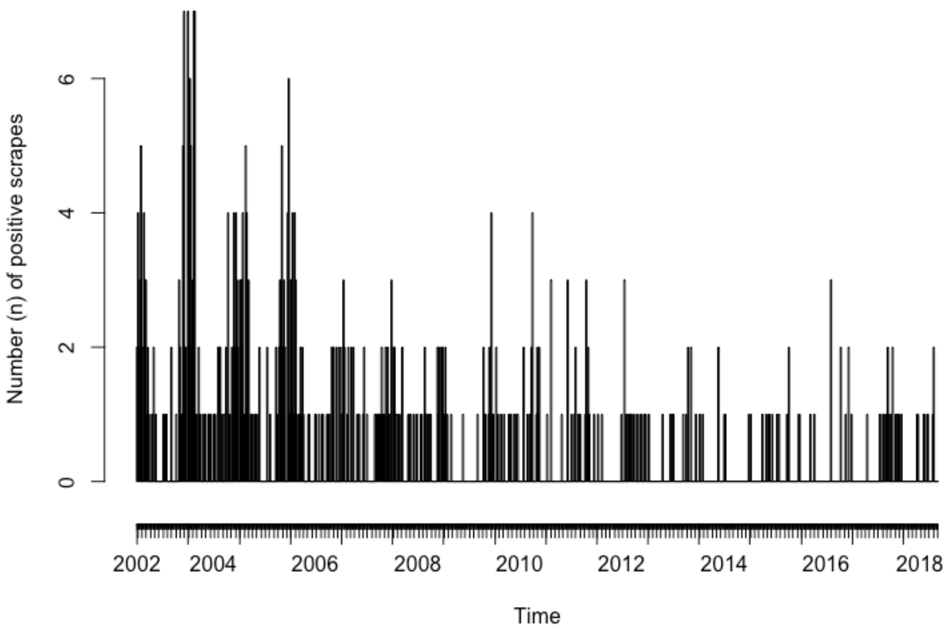


Appendix 2: Number of VIDA positive scrapes per year by month

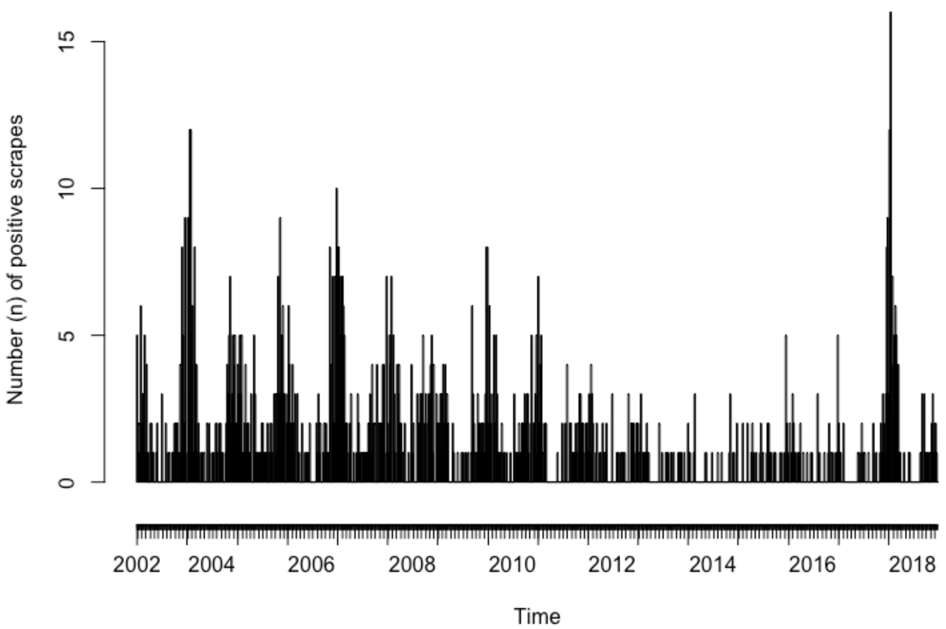
Month	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	TOTAL
January	35	72	33	34	52	28	26	33	34	23	11	13	4	17	18	42	475
February	35	51	32	30	42	26	20	18	19	18	13	6	4	13	8	44	379
March	21	26	31	18	19	13	19	26	10	9	8	5	3	4	3	26	241
April	8	9	19	12	10	16	3	10	5	9	2	2	4	8	3	11	131
May	10	5	12	6	8	3	4	6	1	3	0	3	3	1	2	3	70
June	3	7	7	7	8	7	2	4	2	2	2	1	4	2	2	2	62
July	9	9	8	1	13	10	6	8	4	3	2	2	3	4	4	0	86
August	5	11	9	13	10	11	4	9	11	3	6	4	10	5	2	2	115
September	8	8	7	9	14	20	14	12	6	9	7	3	7	3	3	7	137
October	14	22	20	10	15	13	11	15	9	7	5	5	4	1	7	12	170
November	31	26	34	22	20	18	14	17	13	12	8	8	4	8	6	9	250
December	45	31	37	30	20	19	17	21	9	8	6	8	5	5	10	14	285
TOTAL	224	277	249	192	231	184	140	179	123	106	70	60	55	71	68	172	

Appendix 3: Weekly counts of VIDA positive scrapes from 2003-2018

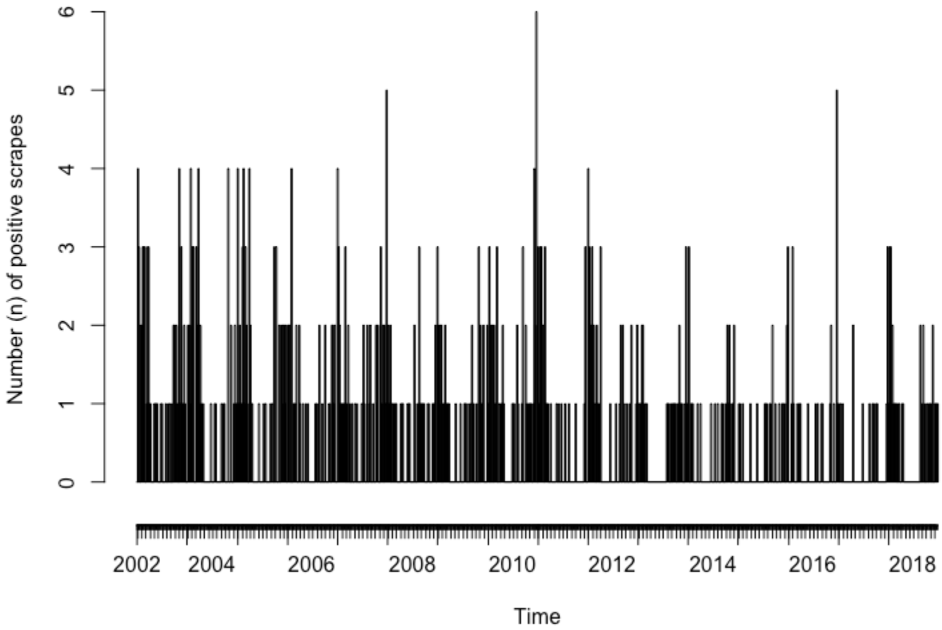
A) England



B) Wales



C) Scotland


Number (n) of positive scrapes
0
1
2
3
4
5
6
2002
2004
2006
2008
2010
2012
2014
2016
2018
Time

Appendix 4: Sheep scab ELISA submission form

A) Page 1

Sheep scab ELISA testing submission form

Date sent:	**Farmer details:**
Veterinary Practice:	**CPH/ Holding Number:**
Tel:	**Tel:**
Email:	**Email:**

Reason for testing: (please circle)
Diagnosis in itchy sheep Monitoring in clinically normal sheep Quarantine…….Other – please specify

For monitoring at flock level: Please collect 1 x red top vacutainer from 12 sheep from the same management group. Please include any sheep with fleece loss or pruritus.

Please complete the short survey below so we can interpret the test results.
Farm type (please circle): lowland upland hill **Flock size**: number of breeding ewes

Scab control strategy:
When were the sheep from which blood samples have been collected last treated with a product active against sheep scab? Product Date

In the past 12 months which of the following were used in your flock? If used primarily for control of other parasites e.g. ticks, worms please state.
OP dips: not used / used
If used please circle which month(s) and indicate if for scab control or control of other parasites
Jan Feb Mar Apr May June July Aug Sept Oct Nov Dec

OP showering: not used / used
If used please circle which month(s) and indicate if for scab control or control of other parasites
Jan Feb Mar Apr May June July Aug Sept Oct Nov Dec

Injectable macrocyclic lactone products: not used / used
If used please circle which month(s) and indicate if for scab control or control of other parasites
Jan Feb Mar Apr May June July Aug Sept Oct Nov Dec

Farm boundaries:
Are all boundaries double fenced where there may be contact with other livestock? Yes / No
Is common grazing used? Yes / No

Please circle any of the following that apply to your flock:
Use contract shearers Contract dippers Share gathering facilities Share livestock trailers

Please list any other management factors that may allow contact (direct or indirect) between your sheep and others sheep:

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email: hihealthflockcare@biobest.co.uk www.biobest.co.uk

Please note that the services performed by Biobest are subject to the Biobest Terms & Conditions of Supply which were updated on the 1st June 2009 and which are deemed to be incorporated into this contract. For a copy of these terms and information concerning the test methods employed, sample requirements and test pricing please contact Biobest or visit www.biobest.co.uk.

Biobest hold ISO:17025 accreditation for a number of our tests. A copy of our current schedule of accreditation can be found on our website at www.biobest.co.uk/about-us/quality

B) Page 2

Quarantine actions:
Are purchased sheep treated for scab on arrival? Yes / Sometimes / No / not applicable
If yes, with what?
How long are purchased sheep kept separate from the home flock?

Are sheep returning from tack treated for scab on return? Yes / Sometimes / No / not applicable
If yes, with what?
How long are returning sheep kept separate from the home flock?

Are sheep returning from marts treated for scab on return? Yes / Sometimes / No / not applicable
If yes, with what?
How long are returning sheep kept separate from the home flock?

Are sheep returning from shows treated for scab on return? Yes / Sometimes / No / not applicable
If yes, with what?
How long are returning sheep kept separate from the home flock?

Has sheep scab been diagnosed in your flock in the previous 2 years? Yes / No

Has sheep scab been suspected in your flock in the previous 2 years? Yes / No

Eartag ID	Breed	Age	Itchy / fleece loss (Y / N)	Biobest Ref	Sample type	Sheep Scab ELISA	Other test requests: e.g. trace element analysis, metabolic ewe profile, other serology, parasitology
					Blood	✓	
					Blood	✓	
					Blood	✓	
					Blood	✓	
					Blood	✓	
					Blood	✓	
					Blood	✓	
					Blood	✓	
					Blood	✓	
					Blood	✓	
					Blood	✓	
					Blood	✓	

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Appendix 5: Example of a 12-sample sheep scab ELISA result report

<u>268227</u>	06-Mar-2019		
2585166			
Result		1	18
2585167			
Result		1	14
2585168			
Result		1	22
2585169			
Result		1	11
2585170			
Result		1	12
2585171			
Result		1	14
2585172			
Result		1	40
2585173			
Result		1	20
2585174			
Result		1	11
2585175			
Result		1	15
2585176			
Result		1	22
2585177			
Result		1	51

Appendix 6: Fields digitised from the sheep scab ELISA submission forms.

* denotes variables that were captured but not subsequently and further analysed in this thesis.

Field	Description
Holding number*	The unique county parish holding (CPH) number of the submitting holding, captured to parish level to maintain anonymity.
Postcode*	Postal code of the holding.
Vet practice	Submitting veterinary practice.
Reason for testing*	Reason for submission. Reasons included: diagnosis for itchy sheep (clinical signs), monitoring clinically normal sheep, testing quarantined sheep, and 'other'.
Farm type*	Primary land type of the holding: hill, upland, lowland, or a combination of the three.
Flock size	Number of breeding ewes
Date of last acaricide treatment	Date of last product used against sheep scab
Last acaricide product given	Product used (brand name or compound)
Use of organophosphate dip	Was an organophosphate dip used within the past 12 months?
Month of last organophosphate dip	If given in the last 12 months, in what month was the product administered?
Use of organophosphate shower	Was an organophosphate shower used within the past 12 months?
Month of last organophosphate shower	If given in the last 12 months, in what month was the product administered?
Use of injectable macrocyclic lactone	Was an injectable macrocyclic lactone product used within the last 12 months?
Month of last injectable macrocyclic lactone use	If given in the last 12 months, in what month was the product administered?
Double fencing*	Are all farm boundaries double fenced where there may be contact with other livestock?
Common grazing*	Is common grazing used?
Contract shearing*	Are contract shearers used?
Contract dipping*	Are contract dip operators used?
Shared gathering facilities*	Are shared gathering facilities used?
Shared livestock trailers*	Are shared livestock trailers used?
Other management factors allowing contact with other sheep*	Free text area to list other management factors and potential risk factors not listed on the form. Also lists any schemes or vouchers for free or subsidised submissions.
New stock – treatment upon arrival	Are new stock treated with a product active against sheep scab upon arrival?
New stock – treatment product	If yes, what treatment product is used upon arrival? (brand or compound name)
New stock- quarantine period	How long are purchased sheep kept separate from the home flock?
Treatment – Tack	Are sheep treated upon return from tack?

Field	Description
Treatment product – Tack	If sheep are treated upon return from tack, what product is used?
Quarantine – Tack	How long are sheep quarantined for upon return from tack?
Treatment – Mart	Are sheep treated upon return from the mart?
Treatment product – Mart	If sheep are treated upon return from the mart, what product is used?
Quarantine – Mart	How long are sheep quarantined for upon return from the mart?*
Treatment – Shows	Are sheep treated upon return from shows?*
Treatment product – Shows	If sheep are treated upon return from shows, what product is used?*
Quarantine – Shows	Are sheep quarantined upon return from shows?*
Sheep scab previously diagnosed*	Was sheep scab diagnosed in the 2 years prior to submission?
Sheep scab previously suspected*	Was sheep scab suspected in the 2 years prior to submission?

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