



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

## Creating an innovation ecosystem for rapid diagnostic tests for livestock to support sustainable antibiotic use

**Citation for published version:**

Bruce, A, Adam, KE, Buller, H, Chan, KWR & Tait, J 2021, 'Creating an innovation ecosystem for rapid diagnostic tests for livestock to support sustainable antibiotic use', *Technology Analysis and Strategic Management*. <https://doi.org/10.1080/09537325.2021.1950678>

**Digital Object Identifier (DOI):**

[10.1080/09537325.2021.1950678](https://doi.org/10.1080/09537325.2021.1950678)

**Link:**

[Link to publication record in Edinburgh Research Explorer](#)

**Document Version:**

Publisher's PDF, also known as Version of record

**Published In:**

Technology Analysis and Strategic Management

**General rights**

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

**Take down policy**

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact [openaccess@ed.ac.uk](mailto:openaccess@ed.ac.uk) providing details, and we will remove access to the work immediately and investigate your claim.





## Creating an innovation ecosystem for rapid diagnostic tests for livestock to support sustainable antibiotic use

Ann Bruce, Katherine E. Adam, Henry Buller, Kin Wing (Ray) Chan & Joyce Tait

To cite this article: Ann Bruce, Katherine E. Adam, Henry Buller, Kin Wing (Ray) Chan & Joyce Tait (2021): Creating an innovation ecosystem for rapid diagnostic tests for livestock to support sustainable antibiotic use, *Technology Analysis & Strategic Management*, DOI: [10.1080/09537325.2021.1950678](https://doi.org/10.1080/09537325.2021.1950678)

To link to this article: <https://doi.org/10.1080/09537325.2021.1950678>



© 2021 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group



Published online: 09 Jul 2021.



Submit your article to this journal [↗](#)








View related articles [↗](#)



View Crossmark data [↗](#)

# Creating an innovation ecosystem for rapid diagnostic tests for livestock to support sustainable antibiotic use

Ann Bruce <sup>a</sup>, Katherine E. Adam <sup>a</sup>, Henry Buller <sup>b</sup>, Kin Wing (Ray) Chan <sup>b</sup> and Joyce Tait <sup>a</sup>

<sup>a</sup>Innogen Institute, Science Technology and Innovation Studies, School of Social and Political Science, University of Edinburgh, Edinburgh, UK; <sup>b</sup>College of Life and Environmental Sciences, Department of Geography, University of Exeter, Exeter, UK

## ABSTRACT

Antimicrobial resistance (AMR) is one of today's greatest public health threats and reducing antimicrobial use in livestock is essential to prevent its spread, requiring rapid diagnostic tests (RDTs) to ensure that the drug prescribed matches the sensitivity of the disease organism. However, despite decades of research on RDTs and a relatively permissive regulatory environment in the UK, few devices are in commercial use. Challenges discussed by RDT developers included identifying commercially-viable targets, and management of the innovation ecosystem, e.g. to create clear pathways to market supporting positive interactions between farmers, vets, and other actors along the value chain. Future support for RDT development could be provided through incorporation in: assured food systems; business service packages provided by centralised laboratories; or animal health monitoring packages related to the spread of AMR. Breeding stock sales could require an accompanying health package including RDTs, vaccines and/or antibiotics, linking to precision agriculture approaches. Unlike the example of RDT development for COVID-19, it seems that the urgency of the issue and the clarity of links between animal and human health outcomes are not yet sufficient to support a fast-tracking programme for the development of RDTs to combat AMR.

## ARTICLE HISTORY

Received 15 January 2021  
Revised 13 May 2021  
Accepted 23 June 2021

## KEYWORDS

Antimicrobial resistance; livestock; rapid diagnostics; point-of-care diagnostics

## Introduction

Antimicrobial resistance (AMR) has been identified as one of the greatest public health threats of our time (O'Neill 2015). Reducing antimicrobial use in livestock has been proposed as an essential strategy to combat AMR in animals and humans (World Health Organisation 2017). However, antibiotic use is sometimes necessary, leading to challenging decisions that balance the immediate health and welfare of animals against the longer-term risk of AMR (Rushton 2015). The COVID-19 outbreak, although viral, has led to increasing use of antibiotics in treatments and has strengthened this focus on AMR (Hsu 2020).

Although policy initiatives and information campaigns have led to large reductions in antibiotic use by the UK livestock industry (UK-VARSS 2020), further reductions are likely to require new approaches. The use of rapid diagnostics to enable more discriminating use of antibiotics is one such approach (O'Neill 2015). Although this is an attractive prospect, there are few products

**CONTACT** Ann Bruce  ann.bruce@ed.ac.uk;  @AnnBruce

© 2021 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group

This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (<http://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited, and is not altered, transformed, or built upon in any way.

within the veterinary sector on the market at present, despite many attempts at developing such devices. Our research sought to understand why this is the case and what barriers are faced by those developing rapid veterinary diagnostics. We argue from our findings that lack of commercialisation has been at least partly due to the lack of a coherent innovation ecosystem and therefore propose such an approach to enable the emergence of future value chains targeting viable markets.

A clear vision for the role of rapid veterinary diagnostics (Borup et al. 2006) was first applied to outbreaks of livestock diseases such as Foot and Mouth Disease in 2001 (King et al. 2010), and revisited during concerns around antibiotic resistance (O'Neill 2015). It was reinforced by the availability of data from precision agriculture (Neethirajan et al. 2017), and is now emphasised in the field of human medicine by the need for a rapid, easy-to-use diagnostic for COVID-19. There is however an important distinction between rapid tests for a viral target (such as Foot and Mouth disease or COVID-19), which detect the presence or absence of a pathogen, and tests to inform decisions about antibiotic use, which need to answer several questions as follows (Okeke et al. 2011). Is this a bacterial infection? What type of bacterium is involved? What existing resistance might be present? Which antibiotics will be most effective for treatment? It is this latter use in informing future antibiotic use that is of interest in this paper.

Several different terms are used for such devices, including rapid, point-of-care or pen-side tests. For clarity, in this paper we will refer to rapid diagnostic tests (RDTs) for livestock and more specifically for our focus on diagnostics to help with antibiotic use, as Rapid Diagnostic Tests for Antibiotic Use in Livestock (RDT-ABL).

Much of the research on antimicrobial prescribing and administration in livestock production has focussed on the behaviour of vets and farmers (e.g. Coyne et al. 2016; Bourély et al. 2018; Buller et al. 2020; Chan et al. 2020). Comparatively little attention has been paid to technologies that could change the basis of future decision making on disease diagnosis and antimicrobial treatment (exceptions are Evers, Aerts, and De Tavernier 2008, an ethical evaluation of RDTs, and Mohr et al. 2020 focusing on sheep scab). This paper considers the potential role of RDT-ABLs in supporting these decisions and explores how the innovation ecosystem could be tailored to facilitate their future development.

## Background

### *Antimicrobial use in the veterinary sector*

Veterinarians and farmers will make precautionary decisions about antimicrobial use in the animals under their care if the risks to the health and welfare of the animal(s) of withholding treatment outweigh for them the longer term societal threat of AMR (Adam 2019). RDT-ABLs may therefore help to reduce the use of antibiotics where animals are free from pathogenic bacteria, provide reassurance to vets and livestock keepers in decisions to withhold preventive treatment, and in some cases ensure that the most appropriate antibiotic is prescribed. In certain clinical scenarios, rapid initiation of antibiotic treatment is essential for health, welfare and production reasons, e.g. a life-or-death scenario such as sepsis in cattle requires the use of broad-spectrum, critically important antibiotics (Pardon and Deprez 2018) and RDT-ABL could help to speed up diagnosis and initiation of treatment in these situations.

Studies from the UK (Chan et al. 2020), other European countries (De Briyne et al. 2013) and New Zealand (McDougall, Compton, and Botha 2017) have found that veterinarians make limited use of diagnostic testing to support antimicrobial prescribing, indicating that this is an issue of international concern. The cost and time required to deliver a result from currently available laboratory tests are major barriers to their use. Antimicrobial prescription on the basis of clinical observations rather than microbiological testing is the norm. This reliance upon clinical observation might lead to inadvertent overuse or, in some cases, erroneous use of antibiotics. The availability of RDT-ABLs could create an opportunity to revolutionise farmer and veterinary decision making about antibiotic use.

Innovation in RDT-ABLs is taking advantage of developments in biology, physics and information technology, adopting a number of different approaches to detect diseases for a range of different livestock species. However, the innovation ecosystem within which these diagnostics are being developed is complex, involving a range of different players and relationships in the value chain, an unclear regulatory environment, with no current regulation of rapid veterinary diagnostics in the UK, unclear paths to market and potentially poor returns on investment (Boon and van Merkerk 2009). This paper examines whether these relationships and the nature of the innovation ecosystem for RDT-ABLs can explain why so few devices have become commercially available.

Networks and social relationships, both formal and informal, are key components of an innovation ecosystem, often embracing trust and tacit knowledge (Scaringella and Radziwan 2018), and Adner (2006) advocates taking a strategic approach to developing an innovation ecosystem. Papaioannou, Wield, and Chataway (2009, 319) refer to innovation ecosystems as ‘a complex network of interdependent relationships’ that allow collaborating firms to create value in ways that no single firm could undertake (Durst and Poutanen 2013). For RDT-ABLs, the most salient feature seems to be to address ‘integration risk’ (Adner 2006, 4), understanding which intermediary actors in the value chain have to adopt, and if necessary adapt, the technology before it reaches the end user. For some researchers, it is critical to examine the structure of the innovation ecosystem and how this system creates and delivers value (Walgrave et al. 2018; Wield et al. 2017). As well as appropriate artefacts and key partners, a suitable socio-technical environment involves the habits and rules that govern ecosystem relationships (Walgrave et al. 2018). It is these relational aspects of the innovation ecosystem, that we suggest are either absent or nascent in the RDT-ABL innovation ecosystem leading to a lack of shared norms and cultures.

RDT-ABLs seem unlikely to be able to create value in a market as individual artefacts or to fit immediately into existing laboratory and veterinarian processes of diagnosis. They have the potential to complement current practices but also to compete with them, and indeed they could be viewed as transformative technologies, opening up path-breaking opportunities (Tait and Wield 2019) for more systemic farm animal health management, but this would require network relationships and ways of working to be restructured.

### ***Rapid diagnostic devices***

There are a number of variables: (i) different rapid diagnostics (e.g. lateral flow devices, portable polymerase chain reaction, microarrays, linking data to mobile phone apps) (ii) different samples (e.g. saliva, blood, milk, urine); (iii) different diseases with diverse characteristics (e.g. contagious bacterial diseases or diseases caused by parasites); (iv) different species (e.g. dairy cattle to poultry); (v) different production systems (e.g. indoor pig production to hill sheep), as well as different stakeholder perspectives. Diagnostics could target single diseases or be multiplexed to allow testing for several diseases at the same time. Some devices (such as lateral flow devices) are self-contained while others require the addition of specific reagents. Both the diagnostic device sector and the livestock sector they could serve are therefore very heterogeneous, and identifying a suitable target product profile is challenging (Belkum et al. 2019).

## **Materials and methods**

### ***Data collection***

Identifying companies developing RDT-ABLs was challenging, reflecting the fragmented nature of the industry and lack of a central contact point for diagnostic developers working in this area. Participants were identified and approached via four major channels; internet searches, networking at relevant meetings and conferences, snowballing through contacts, and word of mouth. Data collection took place from April 2018 to October 2019.

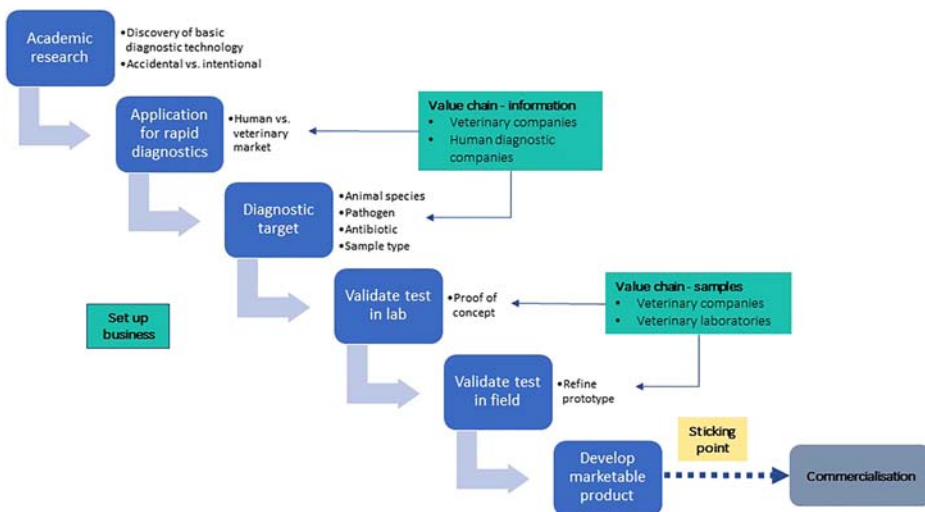
Telephone interviews were conducted with representatives of fifteen diagnostic developers and four industry organisations, veterinary laboratories and government. Interviews were all conducted by author KA with author AB additionally present at three interviews. Fifteen of the nineteen interviews were recorded and transcribed for analysis. Recording failed for technical reasons in one interview and three participants declined consent to be recorded, but agreed to an informal discussion to support the research. No further interviews were conducted when the research team was satisfied that data saturation had been achieved. The research gained ethical approval from the University of Edinburgh.

Participants thus represent a convenience sample of diagnostic developers, with substantial diversity among the individuals, businesses and technologies included. The fifteen developers comprised eleven individuals working in academia, spin-out or start-up companies related to veterinary diagnostics, and four from multinational animal health companies. Twelve different types of RDTs were represented, including phenotypic tests to detect bacterial growth, genotypic tests to detect genetic material from pathogenic bacteria and viruses, and biomarker tests to detect immune responses to infection. The end product in development by all companies was either a reader-cartridge model, where a disposable cartridge containing a sample would be analysed by a multiple-use reader to provide a result, or a single-use, disposable test. One company was developing a sample preparation product to be used in conjunction with other diagnostic tests.

Finally, a stakeholder workshop was held in October 2019. Nineteen participants attended the workshop, of which eight were interviewees or another representative of companies included in the interviews. Ketso kits ([www.ketso.com](http://www.ketso.com)), a hands-on workshop facilitation tool that utilises reusable, coloured shapes to structure the discussion, capture ideas and allow all stakeholders to contribute, were used for small group discussion to identify key points around the pathways to market for RDT-ABLs.

## Data analysis

Data were analysed using the Strategic Analysis of Advanced Technology Innovation Systems (STRATIS) framework (Wield et al. 2017), developed for assessment of innovation ecosystems. The framework pays particular attention to the extent to which an innovation is disruptive or incremental for the business models of companies in the value chain and the resulting policy, regulatory and



**Figure 1.** Summary diagram of pathway for development of market for AMR-RDT-Ls.

innovation support needs of the companies involved. Banxia Decision Explorer software,<sup>1</sup> a software package that allows causal connections to be made among activities, was used to create a map of each company's development process from the interview data. All of the maps were then consolidated, and are summarised to create an overview of the innovation ecosystem for RDT-ABLs (Figure 1). This shows the steps required to take a device from academic research to market, and indicates some of the relationships required in the value chain. Figure 2 shows more detail of the requirements from manufacturing to achieving the goals of innovation. The following sections will discuss the content of these figures in more detail. Quotes from interviews are used to exemplify and expand the analysis, and are indicated in italics.

## Results

### Company business models

Innovation in most of the companies we interviewed was initially driven by the technology they are developing rather than by user demand. We identified three main types of organisation developing RDTs; university spin-outs who have developed novel technologies; companies in other areas (e.g. chemicals) looking for alternative uses for their products; and animal health companies, often working internationally and already selling laboratory-based diagnostics. The animal health companies were seeking new products developed in universities and smaller companies. The former two types of company have limited experience of the livestock sector. However, the livestock sector is perceived as attractive due to fewer regulatory requirements and hence quicker access to market than applications to human health. Several of the developers therefore envisage using the veterinary market as a prelude to developing devices for the more lucrative human market, with the livestock sector providing an income stream and experience with the diagnostic that will enable them to remain in business while seeking to access the human market:

"The reason we're interested in the veterinary side is because of its lower regulatory barriers at the moment it does offer a route towards getting a product more rapidly, certainly getting instruments into trials and beginning to see how well it works much more easily than it is with human clinical labs." (interview G, diagnostic developer)

As noted earlier, livestock production is a very heterogeneous industry sector, making identifying the target market and its overall size challenging, exacerbated by the lack of (i) accessible data on the number of relevant veterinarians or veterinary practices, and (ii) data on key diseases. There is considerable uncertainty about treatment decisions where a rapid diagnostic test would be advantageous. Securing the funding to bring a product to market has the usual 'valley of death'

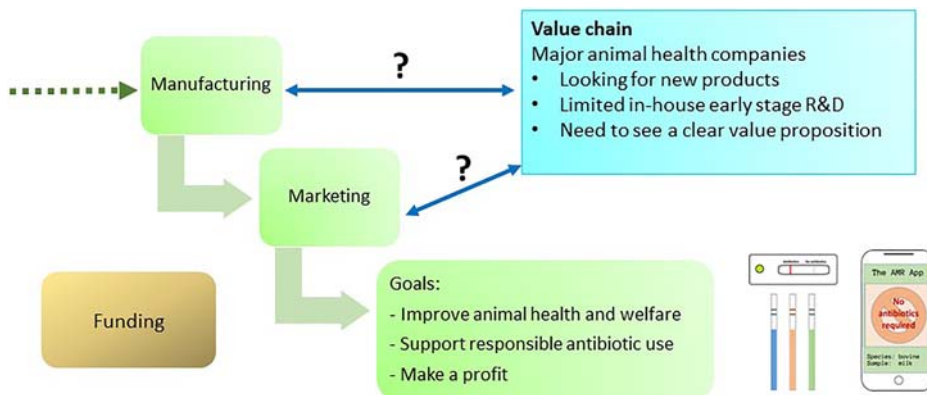


Figure 2. Anticipated next steps in RDT-ABL development and commercialisation.

challenges (Omidvar et al. 2014), as reflected by our interviewees. However, making the case for further funding is complicated by this lack of obvious target markets.

The route to market envisaged by our respondents often involved engaging with other businesses in the value chain, such as veterinarians and farmers, as they recognised the importance of creating these links. The value chain represents the organisations required to bring the product successfully to market.

## **Value chain**

### **Business interactions**

None of the companies interviewed had processed beyond the validation stage at the time of the interviews (Figure 1). Anticipated next steps would be to market and manufacture the product, either following acquisition or in partnership with a major animal health company (Figure 2). Our data suggested that animal health companies were indeed being approached by developers, although RDTs also presented numerous challenges to them too. Most of the technologies they were being asked to consider still required considerable development. The financial risk associated with bringing a product to market is considerable, and companies needed to be confident that the product would be profitable. Furthermore, a company's incentive to invest in the diagnostic will be influenced by their existing product profile and distribution channels, along with manufacturing costs. This dilemma for animal health companies is reflected in the following quote:

“... we always ask ourselves, should we invest right now in this early stage or not, and most of the time it's a no because we cannot see any kind of positive return on investment” (interview L, animal health company)

A further feature in the diagnostics ecosystem is the apparent unwillingness of human healthcare companies to be involved in the veterinary world for fear of risking their brand by being implicated in a potentially controversial but much smaller market sector:

“So just for context, in Europe the veterinary medicines industry, just medicines now, is worth 2.5% of the human medicines industry. UK is a little bit more, it's 4% in the UK but in the EU as a whole it's 2.5%. I'm sure diagnostics is probably going to, the market share in size is going to be very similar or not going to differ radically” (interview N, animal health industry organisation)

Some of our respondents were investigating alternative business models including a focus on providing a sample preparation service or integrating rapid diagnostics with the growing set of precision agriculture technologies (e.g with robotic milking or automatic monitoring of housed livestock).

We conclude that despite the large number of innovative developments in RDT-ABLs, a clear pathway to market is lacking. Finding the right partners to bring these devices to market, and indeed ascertaining the potential size of the market are ongoing challenges within the innovation ecosystem.

That being said, the value chain for rapid diagnostics also involves veterinarians and farmers, and many diagnostic developers are already working with vets/farmers attempting a co-innovation approach, including engaging with them in field trials.

### **Veterinarians**

Veterinarians are not just potential end users for rapid tests, but also an active part of the development process (Figure 2). Most of the smaller diagnostic companies have limited experience of the animal health sector and have worked with veterinary companies to obtain relevant information. Veterinarians have also provided samples for test validation and feedback on prototypes of novel tests.

The process of running field trials with veterinary companies is complicated by the need to work with veterinary and farming businesses and to integrate the validation of rapid diagnostics into their



processes. Several companies reported they had found it difficult to connect with veterinarians and farmers for test validation.

The potentially ‘path-breaking’ nature of rapid diagnostics challenges the currently dominant practice of using laboratory standards of accuracy. Buller et al. (2020) found that veterinarians expressed doubts about the way in which rapid diagnostics would be used in practice and the interpretation of the resulting data. The current comparator tests, laboratory-based diagnostics, raise a high-quality barrier for any competing technology, and there is not yet a strong market demand for the additional advantage of speed in delivery of results from RDT-ABLs. Even if the devices were appropriately sensitive, specific and robust, there would still be the potential for users to draw wrong conclusions from the test and to devalue veterinarians’ expert clinical judgement:

“I think convincing some but not all vets and farmers that the test is valid, even after you’ve gone through trials, these types of diagnostics have always been lab done and people tend to trust labs and I can sort of foresee this trust being problematic” (interview E, diagnostic developer)

Encouraging use of RDT-ABLs may require veterinarians and central testing laboratories to redefine their business models to generating income from diagnostic tests alongside reduced antibiotic sales. It is clear, however, that RDTs, and particularly RDT-ABLs will not completely replace laboratory testing. The traditional gold standard test to support decisions on antibiotic use is microbiological antibiotic sensitivity testing, where bacteria are grown in a laboratory and then tested against various antibiotics (OIE 2018). This approach offers highly accurate information for treatment decisions around antibiotics, but is time consuming and relatively expensive. On-farm culture is one approach to reduce the time and cost of this type of testing and has been used successfully for diagnosis of mastitis on dairy farms (Viora et al. 2014), but whether this is sufficiently simple and rapid to fulfil the criteria of an RDT-ABL is debatable.

A further question was raised regarding the legal responsibility and professional role that veterinarians have for the welfare of animals in their care. RDT-ABLs used by farmers may provide a challenge to veterinarian’s ability to control the use made of the information from the diagnostics. Similar concerns were expressed by doctors in making lateral flow device pregnancy tests for humans available to the public (Green 1991). However, in the case of RDT-ABLs more control is likely to be retained by veterinarians given they will have control over what antibiotics are prescribed as antibiotics are only available by veterinary prescription. Diagnosis of disease in animals, including diagnostic testing, is defined as an act of veterinary surgery and in the UK can only be performed legally by a registered veterinary surgeon (Veterinary Surgeons Act 1966). Although in practice, many treatment decisions on farms are made in the absence of a veterinary diagnosis (Rees et al. 2019). An official veterinary diagnosis confers legitimacy on the results of a diagnostic test by providing certification, which has important implications for disease control programmes. A rapid test performed in the absence of a veterinarian lacks this official status.

Viewing veterinarians as direct customers of new diagnostic test technologies is unlikely to create a large successful market unless there are more systematic changes in the nature of the market. Thus, RDTs and RDT-ABLs specifically, will need to provide benefits for the value chain and for the farmers at the application end of the chain, potentially requiring re-thinking aspects of veterinary practice:

“That’s a huge challenge here for veterinary practitioners, how to be considered ... as a value provider and not as a mandatory pain.” (interview L, animal health company)

RDT-ABLs could be of interest to farmers due to their portability and ease-of-use. Furthermore, farmers potentially represent a far larger market than veterinarians.

### **Farmers**

The perception of the diagnostic developers was that the first challenge to adopting rapid diagnostics is for farmers to recognise there is a problem that such devices can address. Farmers can become

used to a specific level of on-farm disease and not perceive it as a problem. Using an antibiotic can in many cases be a lot simpler than requiring an additional diagnostic test step:

“Because it’s easy for him to inject an intermammary tube with antimicrobials. If this is not critical antimicrobials he won’t have any problem from [two retailers] with the specifications, why should it change?” (interview L, animal health company)

Diagnostic developers recognised that decision support will be required by farmers when using rapid diagnostics. The questions for which farmers require answers may be different from those asked by researchers. Farmers are likely to focus on how the diagnostic informs decision making, rather than the specific disease organism and its antibiotic sensitivity. The implication here is that the accuracy from RDT-ABLs may not need to be at laboratory gold standard level but that improving decision making compared to current practice may be enough.

Many developers recognised that on-farm diagnostic use also requires attention to the context in which the device is to be used, for example, tests on milk have to fit into the routines and timings around milking. Developers also understood the need for robustness in devices intended for on-farm use, but the overwhelming consideration was to ensure financial benefits to farmers from using RDTs.

### ***Financial costs and benefits***

Financial benefit will depend on whose perspective is taken. Unless there are appropriate (and transparent) profits across any new RDT-based value chain, it is likely to fail. There are particular challenges with ascertaining the financial benefits to veterinarians (in a novel context) and farmers:

“It depends who you would think of. If it’s a company, the industrial partner let’s say, then it would have to be the profit, that they would sell the test and get good margin on that. If it’s the farmer, for them the cost of the test is a big thing but it would be the side of prevention or the reduction in the use of the drugs. And for the vets, maybe more involvement within the farm, if they have a point-of-care test they would be able to go and advise and follow the whole process. So I think for that it depends which perspective you’re looking at, if it’s the commercial partner or the vets or the farmer” (interview F, diagnostic developer)

The economic case will depend on a number of factors, including the species being considered; for example, an individual chicken is likely to be worth less than the diagnostic test, in which case the test would need to inform decisions at the group level.

A final perspective was questioning who pays for whose benefit. Most visions for the role of RDT-ABLs focus on the benefits to society (reduced, more focussed antibiotic usage) but expect farmers to pay for this benefit. Recognising the public good value of RDT-ABLs could lead to provision of financial or policy incentives for their adoption in practice, facilitated, for example, by retailer programmes for discouraging antibiotic use and encouraging use of RDT-ABLs.

### ***Regulatory environment***

As indicated earlier, an appropriate socio-technical environment is needed for a successful innovation ecosystem (Walgrave et al. 2018; Wield et al. 2017) and regulation, as a critical component of this environment, can dramatically influence innovation trajectories (Tait, Banda, and Watkins 2017).

The regulatory environment for rapid veterinary diagnostics is complex, fragmented and in many cases unclear (with the exception of diagnostics for notifiable diseases, such as Foot and Mouth Disease that are controlled globally by OIE regulations (Howson et al. 2017)). There is no harmonised regulation for putting veterinary diagnostics on the market across the EU, with different countries having different requirements, often associated with the route that products are required take to get to market (e.g. direct to vets, to veterinary distributors or to human pharmacies). Currently, there appears to be no specific regulation in the UK for bringing rapid diagnostics to the veterinary

market. The standard process for indicating efficiency is to validate the device against gold standard laboratory practice and publish the results (e.g. Ferris et al. 2012).

The lack of an obvious regulatory regime in the UK is perceived to be both a benefit and a challenge. Its attraction is that it could enable products to reach the market quickly and at low cost. However, it can also result in nervousness on the part of developers potentially concerned whether they have identified the relevant regulatory regime or not or that a new regulatory regime could be introduced in the future, affecting their business model:

“One of the things that sort of slightly unnerving about the regulatory situation in the UK is that it’s like the black swan problem, you look to see if there are regulations that you need to abide by and can’t find any but that doesn’t mean they’re not there so there’s that kind of fear that something may pop out of the woodwork at the last minute, if there were more formalisation of the procedure that is required, even in its simplest form that would be helpful” (interview A, diagnostic developer)

The current regulatory landscape could also allow poor quality products without good test performance to emerge on to the market, acting as a disincentive for animal health companies to invest in diagnostics, as it can make them vulnerable to competition from inferior products:

“When you are working in the pharmaceutical company and you are so used to all the guidelines, all the good laboratory practice, everything which is framed and regulated and so on, you take good care in demonstrating that what you are doing is good, safe, effective, good performance and so on. But you are competing with a lot of competitors which are launching things without proving anything and just good marketing, ... innovating in a market which is unregulated is sometimes difficult ... So yes some more regulation could decrease the competition from people who don’t have all the means to invest in respecting all the regulations, but on the other way it will push the ones who have the means to invest more because they will have less competitors on the market” (interview L, animal health company)

There are other pertinent standards indicating the quality of the devices being produced, and the processes whereby tests are carried out. These include quality assurance of laboratory practice and the use of kite marks (CE certification) on products that are marketed.

Further relevant regulations (often in the form of standards) are related to the reagents or processes used in the devices (such as products from synthetic biology or nanotechnology), and disposal of wastes, such as plastics involved in devices. One respondent gave evidence of their impact on competitiveness:

“Also, along with everything here there’s also a waste component, Europeans tend to be very sensitive environmentally compared to those of us in the States and so the type of plastic that’s used or how environmentally friendly might enter into the conversation. For instance, our [x] devices, those are all plastic and those get thrown away, we have competitors that have less of a plastic footprint and so in some areas they’re winning where we’re losing because of the environmental factor” (interview O, animal health company)

Regulation could act as an enabler for some types of tests, for example if farmers were required to use a diagnostic test or antibiotic sensitivity before a specific antibiotic could be used as part of assurance scheme rules. This kind of regulation already exists in some places, such as pig production in Denmark (Dupont et al. 2017). A possible regulatory environment for encouraging use of RDT-ABLS consists of both regulation of antibiotic use and developing appropriate standards for safety, quality and efficiency for the development, manufacturing, distribution and use of RDT-ABLS.

## Discussion

The rapid diagnostics sector is full of creative ideas, drawing on recent developments in biology, physics and information technology, mostly embedded in small spin out companies from universities. By ensuring that antibiotic use appropriately matches the antibiotic sensitivity of the target disease organism RDT-ABLS could reduce the potential for AMR to emerge as a result of on-farm animal treatments.

Many of the current developers of RDTs are unfamiliar with the livestock industry and therefore lack appropriate links within the sector and an understanding of relevant pathways to market. Our

research has shown that, even for those who are familiar with the sector, it is not clear what relationships need to be developed, what the needs and interests of different actors are, and how future pathways to market can be created. As few RDT-ABLs exist in commercial practice, there is scope for misunderstanding or misrepresenting the needs of different actors, and also a potential for different visions of the role of RDT-ABLs to create further uncertainty in developing value chains. Technical challenges include identifying a target for the diagnostic that will provide tangible benefits in reducing AMR and hence a viable market for the device. There is perhaps a need for a centralised organisation to provide a point of contact and connection for all businesses and individuals working in this area, such as the Longitude Prize for RDT-ABL development for human applications.

Future prospects for veterinary RDT-ABLs might best be served by re-conceptualising them from a 'black-box' device that replaces laboratory diagnostics and veterinarian diagnosis, to an integrated element of a system to optimise antibiotic use in livestock. It is not sufficient to focus just on the artefact (the diagnostic), consideration also needs to be given to how the overall system creates and delivers value. The 'sticking point' in the development pathway, as identified in [Figure 1](#), is the commercialisation of innovative RDT-ABLs. So far, the benefit to the individual farmer or veterinarian from using a RDT-ABL seems insufficiently clear or understood to create a viable market, despite the broader public good of a reduction in AMR. In future, different value chains and business models could be based on different conceptualisations of the benefits of RDT-ABLs, serving different functions. This would mean extending the concepts for manufacturing and marketing in the value chain depicted in [Figure 2](#) to include wider 'products' than just a diagnostic device. For example, if implemented in ways that farmers would find acceptable and helpful to their decision making:

- they could form part of an assured food system used in partnership with food processors and retailers, or as part of a package of measures used to maintain antibiotic use at very low levels;
- they could contribute to new business services by centralised laboratories combining the rapidity of RDT-ABLs with the quality control expertise of laboratories, able to respond more quickly to questions about which antibiotic is appropriate to use in particular circumstances;
- they could form part of a package for animal health monitoring, where widespread use of diagnostic devices returned to a central location could be used in regional animal health schemes ascertaining the spread of antibiotic resistance;
- breeding stock could be sold together with a health package of vaccines and RDT-ABLs, or antibiotics or vaccines could be sold in conjunction with RDT-ABLs as a total health care package, potentially in conjunction with precision agriculture technologies;
- an One Health approach could be implemented allowing individual farmers or veterinarians to monitor development of AMR among the animals they are exposed to, which could be of interest in managing individual health conditions.

Any new model would require further exploration to establish the drivers and aspirations of relevant actors in the ecosystem.

Regulations, standards and guidelines will play important roles in antibiotic use in livestock and could promote or inhibit RDT-ABL development and uptake. Some supermarkets already require a diagnostic test to allow farmers to use certain antibiotics.<sup>2</sup> However, the impact of this requirement may be that these antibiotics are simply no longer used at all. Such a response could be effective in controlling antibiotic use but would negate the need for RDT-ABLs.

Assurance schemes, such as Red Tractor, or specific processor or retailer standards, can also encourage the use of diagnostics. Whether this is desirable or not is a subject of debate, with some respondents uncomfortable about a purely negative driver, and preferring an approach of promoting the benefits of diagnostics rather than forcing farmers to use them (Alban et al. 2013; Dupont et al. 2017).

The current UK regulations pertaining to livestock RDTs may also change, as wide-ranging regulatory reform is being considered by the UK Regulatory Horizons Council.<sup>3</sup> A complex and time-consuming regulatory system could stifle the creation of markets for RDT-ABLs, but developing appropriate standards for safety, quality and efficacy could provide industry confidence for future investment in the area (Tait, Banda, and Watkins 2017). A consensus based on industry and stakeholders views, developed under the aegis of a body like the British Standards Institution, could provide a clearer and more level playing field for diagnostic developers.

Considering the market model, currently farmers (perhaps via veterinarians) would be expected to pay for the use of the RDT-ABLs while the primary benefit of its use would accrue to society as a whole, perhaps justifying a government financial contribution to this benefit.

Finding a future market for RDT-ABLs in livestock production may appear challenging. However, the value of rapid diagnostics in the COVID-19 pandemic suggests that finding the appropriate opportunity can lead to the rapid growth of a market sector. Valuable lessons will have been learned from the scientific research and regulatory fast-tracking experience gained while developing RDTs for COVID-19 and many will be transferrable to livestock diagnostics. However, the context of a pandemic is very different from that of antibiotic stewardship. The urgency of the AMR issue and the clarity of links between animal and human health outcomes are not yet sufficient to support a fast-tracking programme for the development of RDT-ABLs.

## Notes

1. <https://banxia.com/dexplore/> accessed 30/11/20.
2. <https://www.fwi.co.uk/livestock/health-welfare/livestock-medicines/tesco-milk-suppliers-to-cut-use-of-critical-antibiotics> accessed 30/11/20.
3. <https://www.gov.uk/government/groups/regulatory-horizons-council-rhc> accessed 30/11/20.

## Acknowledgements

This paper draws directly on research undertaken as part of the project: Diagnostic Innovation and Livestock (DIAL): Toward the effective and sustainable application of antibiotics in livestock farming (Project ID: ES/P008194/), funded by the Antimicrobial Resistance Cross Council Initiative supported by the ESRC and the seven UK Research Councils in partnership with other funders. The support of the Economic and Social Research Council and these institutions is gratefully acknowledged. We thank the participants in this research without whom the research would not be possible, and the helpful comments of two anonymous referees.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

## Funding

This work was funded by the Antimicrobial Resistance Cross Council Initiative supported by the Seven UK Research Councils in Partnership with other funders: [grant number ES/P008194/1].

## Notes on contributors

*Ann Bruce* is Senior Lecturer in innovation in sustainable food systems at the University of Edinburgh. She has an interdisciplinary background combining natural and social sciences, with postgraduate degrees in both. She has worked for an international pig breeding company and Roslin Institute prior her current academic position. Her research has included sheep and beef cattle farmers' attitudes to measures of reducing methane emissions, the use of rapid diagnostics in animal and plant health control, and the commercialisation of cloned animals. She is currently working on understanding the development of rapid veterinary diagnostics to reduce antimicrobial resistance (<https://www.diamr.com/>), and the resilience of UK upland sheep and beef production ([www.upland-resilience.org](http://www.upland-resilience.org)). She is also

developing a public engagement tool on cattle breeding for a Horizon 2020 project and understanding crofting practices in the maintenance of biodiverse plant communities.

**Katherine Adam** is a Postdoctoral Research Fellow on the Diagnostic Innovation and Livestock (DIAL) project, which aims to support the development of novel, rapid diagnostic tests to encourage sustainable antibiotic use in farm animals. Her research interests lie in the social, political and economic impact of livestock disease, and the application of the social sciences to improve animal health. Katie trained as a veterinary surgeon at the Royal (Dick) School of Veterinary Studies in Edinburgh and holds a master's degree in Aquatic Medicine from the Norwegian School of Veterinary Science. She has worked in clinical veterinary practice and as a field epidemiologist, researching endemic animal diseases in Scottish agriculture and aquaculture. In 2015, she completed her PhD at the Royal Veterinary College on the future of farm animal practice in the UK in a changing veterinary business landscape. Her postdoctoral work has included a study of vets' and farmers' motivation for disease control on farms as part of the Scottish Government's Strategic Research Programme, and the development of an integrated neonatal survival and sustainable antibiotic plan to reduce mortality of newborn lambs and calves.

**Henry Buller** works principally in the area of non-human geographies, notably animal geographies. He is involved in a number of national and international research projects and professional activities that seek to bring a critical social science understanding to the issue of farm and working animal welfare in contemporary production systems and food supply chains. He also works on issues of wild species re-introduction and upon the conceptual and methodological approaches to social science framings and understandings of human/animal interactions. Henry is currently leading a major collaborative 4-year research project (*DIAL 2017-2021*), funded by the ESRC and other agencies, into the innovative use of diagnostic procedures in farm animal health to reduce antimicrobial use in livestock agriculture. He is also completing, as Co-I, a three-year EU funded consortium research project entitled 'Hennovation', exploring innovative practice-led solutions to welfare issues in laying hen production. Henry is Visiting Professor at the Department of Animal Environment and Health, Swedish University of Agricultural Science (SLU), Uppsala. Until recently, Henry Buller he was an appointed member of the UK's *Farm Animal Welfare Committee (FAWC)* and Chair of the *FAWC/Defra Welfare at Killing* group.

**Ray Chan** is a Human Geographer from the University of Exeter. His research attempts to provide better understandings of the farmers' and veterinarians' diagnostic practices in the UK, pig production in Hong Kong and post-socialist China, and contributes to antimicrobial resistance research from a social science perspective.

**Joyce Tait** is Co-Director of the Innogen Institute (<https://www.innogen.ac.uk/>) and also holds an appointment at Edinburgh's Global Academy of Agriculture and Food Security. She has an interdisciplinary background linking natural and social sciences to support the delivery of innovative technologies with economic and societal benefits. She has worked on: strategic planning for innovation; regulation and standards; and stakeholder influences. Recent research has explored how regulatory adaptation and creative use of standards can contribute to more effective translation of new scientific discoveries to innovative technologies, and ultimately to national and global prosperity. Innovation areas covered by this research include: the circular economy; GM, synthetic biology and gene editing; genetic databases; pharmaceuticals and antimicrobial resistance; cell therapies and regenerative medicine; diagnostic devices; and stratified and translational medicine. Recent appointments include: the Regulatory Horizons Council; the Prime Minister's Council for Science and Technology; the Synthetic Biology Leadership Council (and Chair of its Governance Subgroup); and Governing Board of the Industrial Biotechnology Innovation Centre, University of Strathclyde.

## ORCID

Ann Bruce  <http://orcid.org/0000-0001-5812-5605>  
 Katherine E. Adam  <http://orcid.org/0000-0002-6451-8744>  
 Henry Buller  <http://orcid.org/0000-0001-5652-4434>  
 Kin Wing (Ray) Chan  <http://orcid.org/0000-0001-7729-6098>  
 Joyce Tait  <http://orcid.org/0000-0003-3458-2144>

## References

- Adam, K. 2019. "Balancing Conflicting Demands: Factors Influencing Vets' Choice of Antimicrobial Agent." *The Veterinary Record* 184 (26): 795–797.
- Adner, R. 2006. "Match Your Innovation Strategy to Your Innovation Ecosystem." *Harvard Business Review. Business Spotlight April* 84 (4): 98–107.
- Alban, L., J. Dahl, M. Andreasen, J. V. Petersen, and M. Sandberg. 2013. "Possible Impact of the "Yellow Card" Antimicrobial Scheme on Meat Inspection Lesions in Danish Finisher Pigs." *Preventative Veterinary Medicine* 108: 334–341.

- Belkum, A., T. T. Bachmann, G. Lamp, J. Gorm Lisby, G. Kahlmeter, A. Mohess, et al. 2019. "Developmental Roadmap for Antimicrobial Susceptibility Testing Systems." *Naure Reviews Microbiology* 17: 51–62.
- Boon, W. P. C., and R. O. van Merkerk. 2009. "Prospective Positioning of Industrial Players: the Case of Theranostics." *Technology Analysis and Strategic Management* 21 (4): 471–489.
- Borup, M., N. Brown, K. Konrad, and H. Van Lente. 2006. "The Sociology of Expectations in Science and Technology." *Technology Analysis and Strategic Management* 18 (3–4): 285–298.
- Bourély, C., N. Fortané, D. Calavas, A. Leblond, and E. Gay. 2018. "Why do Veterinarians ask for Antimicrobial Susceptibility Testing? A Qualitative Study Exploring Determinants and Evaluating the Impact of Antibiotic Reduction Policy." *Preventative Veterinary Medicine* 159: 123–134.
- Buller, H., K. Adam, A. Bard, A. Bruce, K.W. (Ray) Chan, S. Hinchliffe, et al. 2020. "Veterinary Diagnostic Practice and the use of Rapid Tests in Antimicrobial Stewardship on UK Livestock Farms." *Frontiers in Veterinary Science* 7: 765.
- Chan, K. W., A. M. Bard, K. E. Adam, G. M. Rees, L. Morgans, L. Cresswell, et al. 2020. "Diagnostics and the Challenge of Antimicrobial Resistance: a Survey of UK Livestock Veterinarians' Perceptions and Practices." *Veterinary Record*. doi:10.1136/vr.105822.
- Coyne, L. A., S. M. Latham, N. J. Williams, S. Dawson, I. J. Donald, R. B. Pearson, et al. 2016. "Understanding the Culture of Antimicrobial Prescribing in Agriculture: a Qualitative Study of UK pig Veterinary Surgeons." *Journal of Antimicrobial Chemotherapy* 71: 3300–3312.
- De Briyne, N., J. Atkinson, L. Pokludová, S. P. Borriello, and S. Price. 2013. "Factors Influencing Antibiotic Prescribing Habits and Use of Sensitivity Testing Amongst Veterinarians in Europe." *The Veterinary Record* 173 (19): 475.
- Dupont, N., L. H. Diness, M. Fertner, C. S. Kristensen, and H. Stege. 2017. "Antimicrobial Reduction Measures Applied in Danish Pig Herds Following the Introduction of the 'Yellow Card' Antimicrobial Scheme." *Preventive Veterinary Medicine* 138: 9–16.
- Durst, S., and P. Poutanen. 2013. "Success Factors of Innovation Ecosystems- Initial Insights from a Literature Review." In *CO-CREATE 2013: The Boundary-Crossing Conference on Co-Design in Innovation*, edited by R. Smets, and O. Irrmann, 27–38. Helsinki: Aalto University Publication Series SCIENCE + TECHNOLOGY 15/2013.
- Evers, J., S. Aerts, and J. De Tavernier. 2008. "An Ethical Argument in Favor of Nano-Enabled Diagnostics in Livestock Disease Control." *Nanoethics* 2: 163–178.
- Ferris, N. P., A. Clavijo, M. Yang, L. Velazquez-Salinas, A. Nordengrahn, G. H. Hutchings, et al. 2012. "Development and Laboratory Evaluation of two Lateral Flow Devices for the Detection of Vesicular Stomatitis Virus in Clinical Samples." *Journal of Virological Methods* 180 (1-2): 96–100.
- Green, K. 1991. "Shaping Technologies and Shaping Markets: Creating Demand for Biotechnology." *Technology Analysis and Strategic Management* 3 (1): 57–76.
- Howson, E. L. A., A. Soldan, K. Webster, M. Beer, S. Zientara, S. Belák, et al. 2017. "Technological Advances in Veterinary Diagnostics: Opportunities to Depay Rapid Centralised Tests to Detect Pathogens Affecting Livestock." *Revue Scientifique et Technique de l'OIE* 36 (2): 479–498.
- Hsu, J. 2020. "How Covid-19 is Accelerating the Threat of Antimicrobial Resistance." *BMJ* 369. doi:10.1136/bmj.m1983
- King, D. P., N. P. Ferris, J. A. Tomlinson, and N. Noonham. 2010. "Plant and Veterinary Disease Diagnosis: a Generic Approach to the Development of Field Tools for Rapid Decision Making?" *EPPO Bulletin* 40 (1): 34–39.
- McDougall, S., C. Compton, and N. Botha. 2017. "Factors Influencing Antimicrobial Prescribing by Veterinarians and Usage by Dairy Farmers in New Zealand." *New Zealand Veterinary Journal* 65: 84–92.
- Mohr, S., R. Beard, A. J. Nisbet, S. T. G. Burgess, R. Reeve, M. Denwood, et al. 2020. "Uptake of Diagnostic Tests by Livestock Farmers: a Stochastic Game Theory Approach." *Frontiers in Veterinary Science* 7: 36. doi:10.3389/fvets.2020.00036.
- Neethirajan, S., S. K. Tuteja, S. T. Huan, and D. Kelton. 2017. "Recent Advancement in Biosensors Technology for Animal and Livestock Health Management." *Biosensors and Bioelectronics* 98: 398–407.
- OIE. 2018. "Manual of Diagnostic Tests and Vaccines for Terrestrial Animals 2018." Accessed June 27, 2018. <http://www.oie.int/standard-setting/terrestrial-manual/access-online/>.
- Okeke, I. N., R. W. Peeling, H. Goossens, R. Auckenthaler, S. S. Olmsted, J.-F. de Lavison, et al. 2011. "Diagnostics as Essential Tools for Containing Antibacterial Resistance." *Drug Resistance Updates* 14: 95–106. doi:10.1016/J.DRUP.2011.02.002.
- Omidvar, O., M. de Grijs, D. Castle, J. Mittra, A. Rosiello, and J. Tait. 2014. "Regenerative Medicine: Business Models, Venture Capital and the Funding Gap." Report to ESRC and InnovateUK, 30th Oct, 2014. <http://www.innogen.ac.uk/downloads/RegenerativeMedicine-BusinessModels-VentureCapital-and-theFundingGap-Oct14.pdf>.
- O'Neill, J. 2015. *Rapid Diagnostics: Stopping Unnecessary Use of Antibiotics*. Accessed December 19, 2017. <https://amr-review.org/sites/default/files/Paper-Rapid-Diagnostics-Stopping-Unnecessary-Prescription-Low-Res.pdf>.
- Papaioannou, T., D. Wield, and J. Chataway. 2009. "Knowledge Ecologies and Ecosystems? An Empirically Grounded Reflection on Recent Developments in Innovation Systems Theory." *Environment and Planning C: Government Policy* 27: 319–339.
- Pardon, B., and P. Deprez. 2018. "Rational Antimicrobial Therapy for Sepsis in Cattle in Face of the New Legislation on Critically Important Antimicrobials." *Vlaams Diergeneeskundig Tijdschrift* 87: 37–46. Accessed July 16, 2018. <https://biblio.ugent.be/publication/8555500/file/8555501>.

- Rees, G. M., D. C. Barrett, H. Buller, H. L. Mills, and K. K. Reyher. 2019. "Storage of Prescription Veterinary Medicines on UK Dairy Farms: A Cross-Sectional Study." *Veterinary Record* 184. doi:10.1136/vr.105041.
- Rushton, J. 2015. "Anti-Microbial Use in Animals: How to Assess the Trade-Offs." *Zoonoses and Public Health* 62: s1.
- Scaringella, L., and A. Radziwan. 2018. "Innovation, Entrepreneurial Knowledge, and Business Ecosystems: Old Wine in new Bottles?" *Technological Forecasting and Social Change* 136: 59–87.
- Tait, J., G. Banda, and A. Watkins. 2017. "Proportionate and Adaptive Governance of Innovative Technologies: a framework to guide policy and regulatory decision making." Innogen Institute Report to the British Standards Institution. <https://www.innogen.ac.uk/reports/1222>.
- Tait, J., and D. Wield. 2019. "Policy Support for Disruptive Innovation in the Life Sciences." *Technology Analysis and Strategic Management*. doi:10.1080/09537325.2019.1631449.
- UK-VARSS. 2020. Veterinary Antibiotic Resistance and Sales Surveillance Report (UK-VARSS 2019), New Haw, Addlestone, Veterinary Medicines Directorate. Accessed November 18, 2010 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\\_data/file/936107/UK-VARSS\\_2019\\_Report\\_\\_2020\\_.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936107/UK-VARSS_2019_Report__2020_.pdf).
- Veterinary Surgeons Act 1966 Statute Law Database. Accessed January 8, 2018 <https://www.legislation.gov.uk/ukpga/1966/36>.
- Viora, L., E. M. Graham, D. J. Mellor, K. Reynolds, P. B. A. Simoes, and T. E. Geraghty. 2014. "Evaluation of a Culture-Based Pathogen Identification kit for Bacterial Causes of Bovine Mastitis." *Veterinary Record* 175: 89. doi:10.1136/vr.102499.
- Walgrave, B., M. Talmir, K. S. Podoynitsyna, G. L. Romme, and G. P. J. Verbong. 2018. "A Multi-Level Perspective on Innovation Ecosystems for Path-Breaking Innovation." *Technological Forecasting and Social Change* 136: 103–113.
- Wield, D., J. Tait, C. Chataway, J. Mitra, and M. Mastroeni. 2017. "Conceptualising and Practising Multiple Knowledge Interactions in the Life Sciences." *Technological Forecasting and Social Change* 116 (3): 308–331. doi:10.1016/j.techfore.
- World Health Organisation. 2017. *WHO Guidelines on use of Medically Important Antimicrobials in Food-Producing Animals*. Accessed January 10, 2021 [https://www.who.int/foodsafety/publications/cia\\_guidelines/en/](https://www.who.int/foodsafety/publications/cia_guidelines/en/).