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HUMANITIES | SOCIAL SCIENCES | BUSINESS

ARTICLE

https://doi.org/10.1057/s41599-019-0220-2 OPEN

Can resistant infections be perceptible in UK dairy farming?

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ABSTRACT This paper interrogates the claim that antimicrobial-resistant infections are rarely encountered in animal agriculture. This has been widely reiterated by a range of academic, policy and industry stakeholders in the UK. Further support comes from the UK's Animal and Plant Health Agency's (APHA) passive clinical surveillance regime, which relies on veterinarians to submit samples for analysis and similarly reports low levels of resistance amongst key animal pathogens. Building on social science work on knowledge-practices of animal health and disease, and insights from emerging literature on non-knowledge or 'agnotology', we investigate the conditions shaping what is known about antimicrobial-resistant infections on farms. In so doing, we find that how on-farm knowledge is produced about resistant infection is concurrently related to domains of imperceptibility or what cannot be known in the context of current practices. The paper discusses the findings of ethnographic research undertaken on an East Midlands dairy farm that highlight the following specific findings. First, farmers and veterinarians, when observing instances of treatment failure, draw on an experiential repertoire that effaces resistances and instead foregrounds the complexities of host-pathogen interaction, or failings in human behaviour, over pathogen-antibiotic interactions. Second, the knowledge-practices of both farmers and veterinarians, although adept at identifying and diagnosing infectious disease are not equipped to make resistance perceptible. Third, this imperceptibility has implications for antibiotic use practices. Most notably, veterinarians anticipate resistance when making antibiotic choices. However, because of the absence of farm level knowledge of resistance this anticipatory logic is informed through the prevalence of resistance 'at large'. The analysis has implications for the existing passive resistance surveillance regime operating in the dairy sector, which relies on veterinarians and farmers voluntarily submitting samples for diagnostic and susceptibility testing. In effect this entrenches farm level imperceptibility and effacement by farmers and veterinarians within the national dairy surveillance regime. However, we also highlight opportunities for providing farm specific knowledge of resistance through the anticipatory logic of veterinarians and a more active regime of surveillance.

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Introduction

Policy responses to the threats posed by antimicrobial-resistant (AMR) infections in human health increasingly encompass proposals to intervene in animal agriculture (Department of Health (DoH), 2011; DoH and Department for Environment, Food and Rural Affairs (DEFRA), 2013; World Health Organisation (WHO), 2015; O'Neill, 2016). This aspiration has manifested primarily in the form of targets for reducing overall levels of agricultural antibiotic use especially of human-critical antibiotics (HCAs). According to the UK's Veterinary Medicines Directorate (VMD, 2017a), the impact of these reduction targets appears potentially significant. Antibiotic use in food animals decreased by 27% between 2014 and 2016 reflecting significant declines in pig and poultry farming, although masking a slight increase in the dairy sector where farmers switched from HCAs to older antibiotics with a larger amount of active ingredient per dose (VMD, 2017a).

Yet despite compliance, industry groups have vocally contested the basis on which these measures have been justified. With the need to achieve antibiotic reductions in animal agriculture overwhelmingly framed in terms of the implications of AMR for human health, agricultural stakeholders have contested the evidence base supporting this link between agricultural antimicrobial use and human health, or rather noting the apparent lack of such evidence (Morris et al., 2016). For example, when challenging the adoption of antibiotic reduction targets in the UK, veterinarians and farming industry representatives were quick to argue that these were not 'evidence based' (British Veterinary Association, 2015), 'made totally devoid of evidence' (Driver in Farmers Guardian, 2016). Also apparent within these contestations is a sense of agriculture being scapegoated for problems of AMR in human health (Buller et al., 2015).

A more compelling justification for action on antibiotic use in agriculture might stem from practical on-farm experiences analogous to human medicine. Historical and popular accounts of AMR imply that human clinical experience of infections resistant to treatment by multiple drugs was instrumental in transforming the public health story of antibiotics from a matter of triumph to one of tragedy and paradox (Bud, 2007; Cannon, 1995; Levy, 2002). Likewise, similar experience with resistant infections in animals could well alter the terms on which action on AMR is debated in the context of farming. Indeed, a recent report for DEFRA highlighted:

> … that a possible contributor to a more informed awareness of the issue and of the place of farming within the wider debate might come from direct experience of resistance amongst animal pathogens on the farm and subsequently prolonged illness or aggravated mortality levels amongst livestock. (Buller et al., 2015, p. 51)B

However, the authors of this study go on to report that:

> While some veterinarians certainly acknowledged the growing concern, others—often within the same production sector—dismissed it as unfounded (Buller et al., 2015, p. 51)

A few in their sample of 32 interviews did speak of finding some antibiotics to be losing potency and sought to change the prescribed medicine, but they were mainly involved in poultry farming and in one case, in pig farming. Equally, our scoping work in UK meetings of experts and stakeholders focused on AMR points to the prevalence of a view that farmers and veterinarians rarely encounter resistant infections and as such believe this is not a problem for animal medicine.[1] These experiential knowledge claims are further supported by the findings of the Animal and Plant Health Agency's (APHA) passive clinical surveillance regime, which reports low levels of resistance for a range of antibiotics across four major mastitis pathogens[2] (VMD, 2017b). This regime involves diagnostic and susceptibility testing of samples submitted by private veterinary practitioners, often following treatment failure.

Claims that infections resistant to treatment are not encountered on farms have political significance and have been readily mobilised by industry actors, such as the Responsible Use of Medicines in Agriculture Alliance (RUMA) and the National Farmers Union when contesting the necessity of government interventions in on-farm antibiotic use (see Science and Technology Committee (Commons), 2014; RUMA, 2014). Subsequently, antimicrobial use in livestock is positioned as having no significant effect on the development of AMR either in human health or in the animals it might be assumed to impact most readily. These preliminary findings raise a key question which we articulate and seek to address through in-depth ethnographic research shadowing farmers and veterinarians on an East Midlands dairy farm. *Why* do dairy farmers and veterinarians largely not encounter antibiotic-resistant infections in farm animals at present? This question interrogates the core assumption that antibiotic resistant infections would be readily perceptible on farms were they present. However, understanding knowledge as necessarily partial and selective, we argue that rather than taking the absence of antibiotic resistant infections in animal health as a given, AMR researchers should be able to scrutinise it as a provisional claim open to revision.

Our approach is informed by a conceptual framework which seeks to address the multidisciplinary audience of this journal and the call for this special collection on Antibiosis. The framework integrates key insights from a large body of social science research in animal and rural studies with an emerging line of work in science and technology studies (STS). The first set of literature highlights the importance of the knowledge-practices and expertise of farmers and veterinarians as they go about the business of identifying, responding to, and managing disease or disease conditions (Enticott et al., 2012; Hinchliffe et al., 2017). While much of this literature focuses on the production of knowledge, certain exceptions identify the ways in which farm level knowledge-practices produce inevitably selective ways of 'seeing' and encountering animal disease (Fortané and Keck, 2015; Law and Mol, 2011). We develop these insights further by drawing on STS literature that engages with non-knowledge, that is the concurrent production of 'domains of imperceptibility' (Murphy, 2006; Murphy, 2013), 'ignorance' (Kleinman and Suryanarayanan, 2012) or what has been called 'agnotology' (Proctor and Schiebinger, 2008).

To date, these social science approaches have not been applied to consider why antibiotic resistance seems largely invisible or absent to farm actors. We therefore extend them in a new direction to examine how the everyday knowledge-practices of animal disease diagnosis and treatment involve the production of domains of perceptibility *and* imperceptibility and the implication of these processes for encountering AMR infections on farms.

Knowledge-practices in agriculture: the production of knowledge and imperceptibility

The concept of knowledge-practice is rooted in an activity-based theory of knowledge according to which how and what humans know is shaped by what we *do*, thus problematizing more familiar accounts of knowledge as located in the mind and represented by what we *think*. This production of knowledge through practice is further shaped by our entanglement with non-human animals and material infrastructures that fundamentally shape what can be done and thus known. The production of knowledge is therefore always situated and selective. This perspective highlights why scientific or technical knowledge give us only a partial picture of a phenomenon, AMR in this instance, and why we need to consider what relevant actors, farmers and veterinarians in this instance, know and how they know it. Second, this view of knowledge also underscores how the production of knowledge corresponds with the production of ignorance. Subsequently, close attention to the situated production of knowledge involves not only the particulars of these practices, but also holds the contingency of knowledge claims to account by attending to their domains of imperceptibility. Our investigation is informed by key insights from literatures relevant to studying knowledge-practices in farming but these are extended through more explicit consideration of the concurrent production of ignorance. It should be noted that we are *not* using 'ignorance' in its pejorative everyday meaning, but in a descriptive sense to capture what is inevitable about all forms of knowledge and knowledge production. In sum, the first strand of literature emphasises why the knowledges of agricultural actors, particularly farmers, need to be taken more seriously in attempts to resolve problems associated with or affecting agriculture (Enticott, 2008; Hinchliffe and Ward, 2014; Wynne, 1996), while the second provides understanding of how and why some elements of a problem remain invisible or unknown (Gross, 2010; Kleinman and Suryanarayanan, 2012; Law and Mol, 2011). We now elaborate on these overlapping strands of research.

In relation to agriculture, the concept of knowledge-practice has been widely used in social science to draw attention to what farmers and other agricultural actors know as they go about their day to day activities of tending to animals, crops, soil, land, water and other elements of the farm environment and business. This ongoing and sustained activity enables a detailed knowledge of the non-human world to be developed, handed down through generations but also dynamic and evolving over time. This research has largely been motivated by an implicit normative agenda that emphases the importance of 'unaccredited', 'non-certified', 'experiential', 'practical', 'lay', 'local', or 'indigenous' knowledges for responding to agricultural problems, and which has all too often been ignored in processes of agricultural modernisation, policy development and implementation (Burgess et al., 2000; Enticott, 2008; Enticott et al., 2012; Morgan and Murdoch, 2000; Morris, 2006; Riley, 2008; Tsouvalis et al., 2000). Attention to the practices of farm situated knowledge production not only highlights the distinctive nature of farmers' knowledges but also its capacity to complement certified knowledge produced through formalised scientific processes. This point is further reinforced in research on formally accredited experts who also work in agricultural spaces, such as agricultural advisors and veterinarians (Eden, 2008; Ingram and Morris, 2008; Proctor et al., 2012; Tsouvalis et al., 2000). Here too, research shows that knowledge embedded in 'the field' (e.g., clinical practice) is distinct from their formal counterparts (e.g., veterinary science), but nonetheless valuable when synthesised (Law and Mol, 2011). Furthermore, this literature is not limited to consideration of the role of humans in knowledge production. It increasingly attends to how agricultural knowledge production is heterogeneous (Holloway and Morris, 2012; Hinchliffe et al., 2017; Morris and Holloway, 2014). In doing so it is recognised that knowledge is collectively produced from a plethora of associations between humans and nonhumans.

The emphasis on farmer, and to a lesser extent veterinary knowledges arises from both the recognition that these actors produce valuable knowledge, and that this knowledge is routinely marginalised in government policy and initiatives. The contested practices of biosecurity have provided one lens through which to examine farmer knowledge-practices and their effacement within policy discourse and initiatives. For example, Enticott has examined how policy representations of 'good' biosecurity, which demand certain spatial orderings to control bovine TB, efface farmers' experiential knowledge of the disordered, complex and multiple flows of agricultural spaces (Enticott, 2008; Enticott et al., 2012). The result is that the policy proposals to achieve biosecurity by closing buildings to wildlife was dismissed as a 'joke' by farmers on the grounds they potentially exacerbate other health risks (Enticott, 2008). Likewise, Hinchliffe and Ward's (2014) work highlights the strategic use of muck by farmers to produce immunity in pigs newly introduced to farms. Such examples demonstrate the experiential knowledge of farmers gained by virtue of managing animals and animal health over time. A different perspective is offered within the work of Fortané and Keck (2015). In writing about the limitations of guidance on biosecurity these authors note that farm surveillance practices not only foster knowledge but also produce and maintain ignorance. We seek to advance this point through introducing insights from the growing body of literature on non-knowledge or 'agnotology' (Proctor and Schiebinger, 2008), 'domains of imperceptibility' (Murphy, 2013) or 'systematic ignorance' (Kleinman and Suryanarayanan, 2012; McGoey, 2007). Rather than cover the breadth of this body of literature, which is primarily interested in the field of toxicology and pollution regulation, we identify two insights that we introduce to the literature on farm-level knowledge-practices.

Firstly, questions around the production of knowledge, what is known and how, should be mirrored by interrogation of the domains of imperceptibility, what cannot be known, on the basis of current practices. Therefore, the privileging of certain approaches to knowledge production leads to a systematic production of ignorance. Secondly, the argument that what cannot be known is central to a politics of knowledge in which the production of certain types of knowledge *and* ignorance is crucial to maintaining dominant political economies of pollution (Kleinman and Suryanarayanan, 2012; Murphy, 2006; Murphy, 2013). This literature thus pays specific attention to how the promotion of certain knowledge-practices and epistemic cultures entrenches specific ways in which toxic objects and phenomena can be encountered (or not), often to the benefit of the status quo. We seek here to bring these insights regarding the production of knowledge and imperceptibility to bear on the mundane farm-level knowledge-practices of animal disease diagnosis and treatment as a means of scrutinising knowledge claims about the absence of antibiotic resistant infections on farms.

In summary, we draw conceptual direction from a range of social science literature that highlights the need to account for the heterogeneity of human and non-human actors shaping knowledge production in situated farm contexts. Following an account of the methods employed in our research, we elucidate how and what farmers and veterinarians know and do about animal disease diagnosis, treatment and prevention. This provides a basis to examine how these actors produce knowledge and ignorance of AMR infections.

Methods

Ethnographic participant observations with farm staff and veterinarians on a dairy farm in the East Midlands of England were conducted over a four-month period between September and December 2017 as part of a broader interdisciplinary study on antimicrobial resistance in agricultural manure and slurry. The focus on dairy farming is justified as follows. Dairy farming is the single largest agricultural sector in the UK, accounting for around

17% of UK agricultural production by value (DEFRA and Rural Payments Agency, 2012) and the third largest agricultural consumer of antibiotics in the UK after pigs and poultry (VMD, 2017a). However, in contrast to pigs and poultry, the dairy sector has seen antibiotic use increase suggesting the practice is more intractable than other sectors. Surveillance of mastitis pathogens[3] is routinely conducted by Animal and Plant Health Agency (APHA) veterinary laboratories. Although primarily a diagnostic service for veterinarians, it also functions to identify new and emerging patterns of resistance that might be clinically relevant (VMD, 2017a). In sum, the dairy sector is an economically significant agricultural sector and site of AMR surveillance and intervention for government antibiotic use policies. Examination of the production of knowledge and ignorance of AMR within dairy farming is therefore of research and policy significance.

The particular dairy farm in which the research work was conducted is a high input, high output farm, housing 200 milking cows and 300 young stock reared as replacements. Cows are housed indoors all year round and the farm employs automated milking robots. Animals are spatially segregated into different buildings or pens within the same building. For young stock this segregation is on the basis of age, i.e., calves, immature heifers and bulling heifers that have begun being inseminated, and for adult cows according to their status within the production system, i.e., dry cows[4], sick cows and milking cows. This farm reflects trends happening across the UK and European dairy sector. For example, although above the average herd size in England of 150 (ADHB Dairy, 2018), there is a long-standing trend towards larger herds in the UK (AHDB Dairy, 2016)[5]. Similarly, robotic milking machines are popular in northern Europe and increasingly so for UK dairy farmers considering investment in new milking parlours (Holloway et al., 2014). Nationally 5% of UK dairy herds are kept wholly indoors (European Commission, 2017) but increased time spent indoors is becoming the norm for dairy cattle with fewer cows being grazed outdoors and for fewer days per year (European Grassland Federation, 2014). As a result, the farm offers an ideal site within which to examine contemporary practices of animal disease diagnosis, antibiotic use and the challenges of AMR in dairy farming, and animal agriculture more broadly.

Due to our alignment with an activity-based theory of knowledge according to which, how and what humans know is shaped by what we *do*, understanding the factors that shape knowledge and ignorance of AMR requires us to pay close attention to the *doing* of animal disease diagnosis, assessment and treatment, and the ways in which these practices inform judgments about the prevalence of resistance. Such practices often operate at the level of the tacit and the taken-for-granted requiring an in-depth approach to data collection. We therefore utilised the ethnographic technique of participant observation on the farm over the course of a 4-month period.

Ethnography has become an established qualitative method in rural research in response to a range of contextual considerations and epistemological reflections that highlight the need for in-depth approaches enabling detailed and prolonged investigation of a particular social context and the situated relations and practices of knowledge production (Hughes et al., 2000). Ethnographic observations often involve extended periods of engagement within a specific research site which limits the capacity for multi-sited studies but provides instead space to explore participant understandings and knowledge-practices, over time and in response to emerging events as these happen (Clark and Emmel, 2010). Furthermore, participant-observation produces opportunities to illuminate habitual or hidden relations and practices that would not be readily exposed through seated interviewing or surveying (Kesuenbach, 2003).

Participant observations with farm staff consisted of two weeks of continuous on-farm observations shadowing staff through their daily work routines in September 2017. This was then followed by repeated engagement and shorter periods of shadowing farm staff throughout the rest of the four-month period on a weekly basis. The farm staff include the farm manager and assistant manager, alongside two herdsmen and a calf technician. The latter was also responsible for the farms record keeping. On Wednesdays veterinarians visited the farm and conducted a general herd health check and sick cow visit and the pregnancy diagnosis check. They were shadowed during these weekly visits over a 4-month period. In addition, vets were also observed during a number of ad hoc visits in response to on-farm animal health developments outside of this routine. Four vets involved in day-to-day animal health diagnosis and treatment assessments and the provision of consultancy advice to the farm were shadowed whilst on the farm.

Observational notes were not limited to animal health diagnosis and treatment but the entire range of on-farm activities since these could potentially shape the use of antibiotics and judgments about resistance. Short hand-written notes were made during observations when feasible. They attempted to catalogue important snippets of conversation, interesting events and general reflections and observations about everyday farm and veterinary practices. All effort was made to transcribe these shorter notes into documents as soon as possible which allowed for further expansion. This also functioned as an initial stage of analysis as the material was organised into broader topic areas to provide structure to these documents. The research focus meant that particular emphasis and attention was given to the on-farm practices of animal health management and incidences of illness and its treatment.

Analysis of these documents was completed with the MAXQDA software package. This involved coding the notes to identify prominent topics from across the data set and salient themes. The data were coded into 13 codes, which structured the data into high level categories, for example relating to the work of particular actors such as Farm Staff (F) and Vets (V). The codes contained numerous sub-codes which reflected the different knowledge-practices of animal health management and different themes within them. What is presented below represents key themes within the data set that relate to on-farm encounters with animal disease, its diagnosis and treatment (including the use of antibiotics), and antimicrobial resistance.

Empirical findings

Our empirical findings are organised as follows. We begin with discussion of disease treatment outcomes because it is here that resistant infections are *theoretically* perceptible to farmers and veterinarians according to our scoping work and Buller et al. (2015). However, since these actors apparently *do not* currently encounter resistant infections, according to our ethnographic work, we aim to scrutinise their interpretations of treatment outcomes such as prolonged illness or aggravated mortality levels amongst livestock under antibiotic treatment.

A treatment outcome is an endpoint of a cascade of events, judgements and interventions in animal health focused upon the sick animal body. Hence restricting our investigation to interpretations of treatment outcomes risks ignoring other important knowledge-practices within which resistance might be made perceptible. We therefore move backwards from farm staff and veterinarians' interpretations of treatment outcomes to examine firstly, the underlying knowledge-practices of disease diagnosis. This reveals the ways in which farmers and veterinarians recognise disease and the implications of this for the production of on-farm knowledge about resistance at the point of diagnosis. Secondly, we examine how diagnostic decisions translate into particular treatment choices including antibiotics and how, if at all, resistance is considered when making such decisions.

Interpreting treatment outcomes

Uncertainty and effacing resistance. Theoretically at least, the farm staff are the key agents for identifying antimicrobial-resistant infections. They are responsible for administering antibiotics to sick animals and they also observe sick animals over the full course of treatment. This close degree of interaction and observation of ill animals means they are potentially well placed to spot instances of treatment failure or prolonged treatment that could be linked to resistance. Contrastingly, veterinarians are only present intermittently and at the farmer's behest.

Indeed, the farm staff and veterinarians had anecdotes that included animal mortality while receiving antibiotic treatment, persistent infections that re-occurred after a seemingly successful course of treatment, and courses of prolonged treatment. However, when asked directly whether they believed antibiotic resistance played a role in these outcomes farm staff and vets expressed significant uncertainty in arriving at resistance as the explanation. As these quotes from different farm staff and vets highlight, there is range of different factors that either confirmed resistance was not a problem, or confounded such a clear interpretation:

> F1: Only once I have ever thought [there] was definitely resistance [and that] was with that premature calf, the antibiotics were just not shifting it [pneumonia]. But then again you could say it was because it was so premature. Most [animals born so prematurely] wouldn't have survived that long anyway
>
> …
>
> F3: I sometimes think that the TD[6] isn't really getting rid of it fully, that there is a bit of resistance, but then you never know is it because of the morphology of the udder, or something else about the cow that is causing it. … Does it just keep sitting in shit? (F3)
>
> …
>
> V6: … the problem is there are an awful lot of other factors that affect treatment outcome as well as resistance profile of the organism so I would say there are vanishingly few situations in which I as a clinician would kind of recognise that I encountered a problem caused by antimicrobial resistance and would make different treatment decisions as a result.

In explaining treatment outcomes, the farm staff and vets referred to the physical and behavioural characteristics of the animals (i.e., a premature calf, a cow that tends to sit in the dirty aisle rather than the beds), and the variance in disease expressions. However, the variability in host-pathogen interactions and animal behaviour was not the only explanation for poor treatment efficacy and higher than normal animal mortality or morbidity as the following quotes illustrate.

> V1: Nuflur[7] has previously had poor efficacy due to administration inconsistencies by the stockperson.
>
> …
>
> Res: So why do you think that farm was having these [animal health] problems?
>
> F2: The manager, he was an idiot. …. Not a good building for cows, or people.

Relations between animals and material infrastructures, and failings in human behaviour were also held responsible.

When interpreting treatment outcomes, the experiential knowledge-practices of farmers and veterinarians produce a diverse repertoire rooted in the complexities of highly variable experiences of animal health, over time and on different farms. Subsequently, while cognizant of resistance as an issue of concern, the complexity of factors accounting for instances of persistent illness or aggravated mortality mean that resistance is largely imperceptible within everyday knowledge-practices employed by farmers and veterinarians and obscured in favour of alternative, equally plausible factors. As such these resistance 'indicators' are not a potentially useful means through which resistance to antibiotics might be made perceptible to farmers, farm staff and veterinarians. These symptoms are not unique to resistance. Instead they can emerge from any number of different on-farm relations, all of which produce functionally similar treatment outcomes and act to efface resistance.

Resistance and herd health oversight. Treatment outcomes are not solely assessed on the basis of individual instances of disease. Herd health reporting contributes to identifying herd wide animal health trends and this oversight can signal situations in which resistance might be implicated. The last time the farm sent samples off for microbial culturing occurred three years prior to data collection. Such action resulted from the identification of a trend, established over two years, of relatively high levels of recurrent clinical mastitis cases within a single lactation, indicating a poor apparent cure rate. Yet, even though this form of testing can make bacterial species and resistance perceptible there remains considerable uncertainty as to the cause of these trends. Initial bacteriology identified a clear environmental aetiology suggesting re-infection pressure, alongside highlighting the casual role of Gram-negative bacteria such as *Enterococcus* and *Klebsiella* which are typically difficult to treat.

Instead of increasing certainty, microbial culture highlights the multiplicity of resistance as a bacteria trait. It can be a potentially inherent or acquired characteristic of bacteria. While only the latter is of policy concern, both have implications for the on-farm experience and interpretation of animal disease. Given a lack of diagnostic knowledge on causal bacteria, instances of the former could efface the other in explaining poor treatment efficacy. Furthermore, it highlights the limitations of herd health oversight for identifying conditions in which resistance might be implicated. This is because a significant period of time can elapse between the emergence of animal health issues potentially linked to resistance, and it being identified as a specific matter of concern for the farm. This has further implications for the conduct of the passive surveillance regime which entrenches these lags and processes of on-farm effacement.

However, treatment outcomes are not the only site at which judgements and interventions about animal health are made and around which resistance might be made perceptible. We will now move backwards from the endpoint of treatment outcomes to consider other sites at which knowledge-practices of animal husbandry might comprehend antimicrobial resistance. We start by examining veterinary and farmers knowledge practices of disease identification and diagnosis.

Identifying and diagnosing animal disease

Even before illnesses come to be treated, farm staff are the frontline actors identifying when an animal is ill in the first place. This happens through their daily engagement with livestock which involves discrete tasks aimed solely at identifying specific diseases, such as the daily mastitis check, as well as from ongoing observation of animals during other farm tasks. As such farmers and their staff possess a considerable body of experiential knowledge regarding animal behaviour, animal health and treatment, individually and as a broader community. Such on-farm knowledge-practices were weighted towards identifying the non-notifiable, routinely encountered diseases that impact on the present and future commercial productivity of the farm, notably, mastitis, lameness and pneumonia in calves.

Mastitis, an infection of the udder, was the principal concern. A daily check was facilitated by the robotic milking machines which flagged individual cows with a high somatic cell count. High cell counts suggest an immune response and potential infection. This illustrates one of the ways in which, when making animal health management decisions, farmers combine their own experiential knowledge practices with other knowledges, in this case produced through milking robots (Holloway et al. 2012). However, high cell count alone does not trigger treatment and further judgement is required. This task fell to F3, who every morning picked out flagged cows, felt their udder to judge its temperature and then drew, by hand, milk into a bucket. Presence of infection was judged on the basis of the milk, its consistency and colour. Specifically, milk had to be perceived as 'thick', or 'snotty' to confirm infection, in which case antibiotic treatment was given. Diagnosis and treatment is therefore conditional on more than one sign of infection. The udders of cows with high somatic cell counts but otherwise normal milk were assumed to have sub-clinical infections. Such instances did not receive antibiotic treatment. Instead a cooling peppermint cream was applied to the afflicted udder quarter(s) to reduce any swelling with the cow's immune system left to manage the sub-clinical infection.

The uncertainties surrounding identification of disease were more pronounced when diagnosing pneumonia in calves.

> F1: Vets say if it coughs then treat for pneumonia but when they are coughing does that mean they have pneumonia or are they just coughing? The clinical signs of pneumonia are fever, nasal and oral discharge, laboured breathing, but if their breathing is laboured then that is it

This uncertainty was confounded by gaps in technological and stockperson oversight. Calves were not subject to the constant technological monitoring provided by the robotic milking machines, nor received the same degree of human attention as the adult cows. This was compounded by a calf rearing shed that was judged as having poor ventilation which increased pneumonia risk. Subsequently, a 'wait and see' approach could condemn a calf. Uncertainty, stemming from the varying forms of disease expression, was contrasted with knowledge about the environments of the farm and their role in producing animal ill health. These broader considerations, alongside the veterinary advice, meant that a 'cough' could be judged to be pneumonia despite concerns that such judgements lead to over-treatment.

However, symptoms of ill health were often less obvious than a visibly coughing animal or discoloured milk, in part due to the cows acting in ways that appear to deliberately mask the signs of illness. Such behaviour required staff to be skilled at identifying the subtler signs of illness. Drawing on tacit knowledge of cow behaviour, individual cow histories as well as attending to the small physical signs such as a change in posture, movement and the look of the eyes, farmers sometimes identified early signs of infection and illness.

> F2: She doesn't look strong and her eyes they look tired, there is something wrong with her.

Indeed, attention to eyes and 'she looks tired' was a repeated explanation for judgements about animal ill health, a point which has also been noted within the broader literature (see Burton et al., 2012; Law and Mol, 2011). These types of assessment highlight how disease can be characterised by ambiguous symptoms but also the difficulty of articulating the experiential knowledge that is drawn upon when identifying these subtle cues. It was these latter, more ambiguous signs of illness that resulted in a farmer calling a vet, particularly if the data from the milking robot suggested a negative change in weight, rumen function or milk yield and they themselves were unable to make a diagnosis.

Over the 4-month period of observations veterinarians' diagnostic knowledge was called upon in instances where farm staff were unable to make a diagnosis, wanted a second opinion, there was a rapid decline in an animal's health, and/or where treatment requires specific veterinary skills outside of a farmers' knowledge-practices, such as surgery. Veterinary clinical examination of animals involves: handling the animal to assess a cow's body internally and externally; audio assessment of certain rhythms, rumen turnover, heartbeat, and breathing; and judging certain smells. As one vet articulated:

> V3: [We are] only as good as our stethoscope and the length of our arm.

Clinical examination was a more formalised process, but judgement and experiential knowledge of animal bodies were crucial to making diagnoses and identifying ill-health. As one vet put it:

> V1: There is a difference between box ticking and actually doing it in a way that might mean you can feel something

In most cases the causative agent, bacterial or otherwise, was inferred through reference to laboratory knowledge of infection. Within the everyday diagnostic practices there was no testing of samples from animal bodies.

Although the testing of bodily samples was not conducted within routine animal health assessments by farmers or veterinarians it is available to them. Indeed, both the UK government, via the APHA laboratories, and private laboratories offer bacteriology and antibiotic susceptibility testing on request. However, when asked about the prospect of taking samples for microbial culturing vets rejected such practices as a useful diagnostic tool on the basis that it was too slow and impacted negatively their ability to meet their professional duties and farmers expectations.

> V2: There isn't time to send something to culture, it's going to be at least 24–48 h before it tells me anything. I need to make a decision there and then, it's what the farmer has got me out for.

As a result, the casual organism and its resistance profile remains imperceptible at the point of diagnosis. This rejection of microbial culture carries further significance because it is this sort of diagnostic activity that currently provides biological samples for the passive AMR surveillance regime operated by the APHA within the dairy industry. However, the APHA labs currently receives a low number of samples leading to a paucity of surveillance data (see VMD, 2017a, 2017b).

Consequently, although farmers and veterinarians are skilled at identifying signs and symptoms of infection on which to make diagnostic decisions, certain characteristics of an infection remain imperceptible to these knowledge practices, most notably regarding the specific casual organism. For instance, mastitis and pneumonia can be caused by a range of gram-positive and negative bacteria, with gram-negative bacteria being inherently more difficult to treat with antibiotics due to their cell wall morphology. As a result, these diagnostic uncertainties and variabilities further contribute to a repertoire for explaining poor treatment outcomes which effaces resistance. Furthermore, the imperceptibility of the causal agent within the context of diagnostic judgements has implications for antibiotic choices, to which we now turn.

Antibiotic choices

The farm retains a bulk supply of core antibiotics (intermammary and intermuscular systemic antibiotics) in order to deal with commonly occurring infections. Choices over which antibiotics to store on the farm were made through negotiations between the farm staff and vets alongside restrictions imposed by the milk contract[8]. Furthermore, these contractual restrictions were being influenced by government stewardship policies placing pressure on veterinarians to move away from prescribing 3rd and 4th generation cephalosporins and fluoroquinolones. This takes the form of contractual covenants asserted by the milk buyer which prevented the use of these classes of antibiotics on the farm. As a result, the farm was moving towards using older antibiotics.

When disease was identified staff followed a ‘script’ about which stored antibiotics to use. For instance, every mastitis infection would receive an intermammary antibiotic, whereas a more serious case would also entail an intramuscular injectable antibiotic. It was entirely at the farmer’s discretion as to what constituted a more serious case. A normal course of treatment for mastitis with intermammary antibiotics was planned to last seven to eight days but anywhere between five and sixteen days was not considered abnormal. This was replicated in other instances where a need for treatment was expected to be relatively routine, for instance pneumonia in calves and dry cow therapy. Resistance was not a meaningful frame of reference when making these everyday antibiotic choices.

Antibiotic choices in instances of disease were more complex for vets due to the following increased array of considerations beyond those of the routine script deployed by farm staff. The first consideration was the spectrum of effect, specifically whether the infection was likely to be caused by gram-negative or gram-positive bacteria. This decision is further complicated by the reality of complex bacterial communities being implicated in infections. Whether an antibiotic and its method of administration is suitable for reaching the site of infection in sufficient concentrations to treat any infection was a second consideration. What antibiotics are licensed for use under the circumstances, and whether a particular diagnosis is judged to merit off-license use, is also crucial. What antibiotics were available on the farm and whether the farmer has personal preferences is a final factor.

Crucially, when making antibiotic choices veterinarians occasionally anticipated the potential for resistant infection:

> V1: So, metritis, we are looking at E. coli, Staph and pyogenes. So, resistance. Relatively good chance of Staph, so might want to consider that [when choosing antibiotics].
>
> …
>
> V3: We know there is quite a bit of resistance around for tetracyclines, it is an old antibiotic plenty of bacteria carry genes for that

Prior to directly experiencing resistance through observing treatment outcomes, vets attempted to make resistance perceptible through anticipation rooted in knowledge about what types of resistant bacteria were potentially circulating on farms. MRSA, and tetracycline resistance were both anticipated because of their documented presence within the environment, and upon other farms. However, these anticipatory considerations were based on resistance being made visible ‘at large’, not on the basis of local knowledge about the studied farm and as such it was not guaranteed to change antibiotic decision making. Equally, during our ethnographic observations, anticipated resistance was never subsequently confirmed, for example through microbial culture of samples. Yet the practice of anticipation suggests there are ways of making resistance perceptible that are not predicated on directly encountering resistance at the site of any specific animal body or through a specific treatment outcome.

Resistance, effacement and imperceptibility

Currently, claims that farmers and vets largely do not encounter resistant infections on farms are predicated on the assumption that resistant infections are perceptible to these actors, if they were present. Our empirical analysis interrogates this assumption and examines *why* dairy farmers and veterinarians largely do not encounter antibiotic resistance at present. Through examining the broader knowledge-practices of animal disease diagnosis, antibiotic choices and interpretation of treatment outcomes, we have highlighted how farmers and vets are not sufficiently equipped to make resistance perceptible. At present, neither their experiential knowledge-practices, nor the technological apparatus available on the farm to make disease visible (milking robots, rumen monitors etc.) enable resistant infections in animals to be detected. Instead resistance is either entirely imperceptible or effaced through an alternative explanatory repertoire used to interpret individual treatment outcomes. This repertoire emphasises the ways in which these outcomes can result from existing on-farm host-pathogen, and human-animal-material relationships independently of resistance being a factor. The complexity of factors contributing to any one treatment outcome, and to its interpretation, obscures resistance.

Attention to the herd level treatment outcomes does provide opportunities to identify conditions in which resistance might be implicated. Yet, there is potential for lag between the emergence of a trend of poor treatment outcomes and it being identified as a matter of concern on the farm. Equally, even when conducted, microbial culturing and susceptibility testing does not translate into a clear story implicating resistance. Instead it draws further attention to the multiplicity of factors entangled in producing poor treatment outcomes.

The imperceptibility of resistance within everyday practices of animal disease diagnosis, its effacement in the interpretation of treatment outcomes and the potential for significant lag in identifying disease trends raises a number of implications regarding dairy sector level surveillance of resistance by the APHA. Most significant is that the effacement and imperceptibility of resistance at the farm level is encoded within the surveillance regime due to a reliance on farmers and vets to submit samples. This raises questions regarding the capacity of this surveillance regime to effectively make farm level resistance visible given that veterinary and farmer knowledge-practices effectively render resistance imperceptible or potentially effaces its significance. A passive surveillance regime is therefore an ineffective means of surveying resistance and its development over time. An alternative, and potentially more effective approach is more active monitoring of on-farm resistance.

However, our analysis also highlights opportunities. In particular, within their knowledge-practices of animal diagnosis veterinarians attempted to grapple with the imperceptibility of resistance through adopting an anticipatory logic of pre-emption (Anderson, 2010). As a result, vets made antibiotic choices in the context of inferring the possible presence of a resistant infection within a specific disease instance. At present, this anticipatory logic was informed by knowledge produced primarily in contexts that are physically and practically distant from the farm. This distance between the spaces of knowledge production on resistance, and the situated contexts within which decisions over sick animals are being made complicates the transition from preemptive logic to action. This is particularly pronounced when experiential judgements of treatment outcomes efface resistance as a potential contributor to negative outcomes. While in theory anticipatory logics create space to legitimise and guide action in the present on the basis of an imagined future (Anderson, 2010), in practice pre-emption did not produce deviation from established antibiotic choices routinely being made on the farm.

Nevertheless, it highlights a means of grappling with the imperceptibility of resistance within everyday farm level practices. The development of a more active surveillance regime which can generate situated knowledge of resistance could be used to inform vets i.e. anticipatory logics. The environmental aetiology of many everyday animal diseases on dairy farms, such as mastitis and respiratory infections, and the entanglement of animals with the environments of the farm, raises the prospect for sampling from animal bodies and across the farm environment - wastes streams, bedding, surfaces of the milking machinery - as a means of actively producing microbiological knowledge on resistance on dairy farms. Such knowledge could potentially further inform veterinary and farmer decisions on antibiotic choice, particularly the formers' anticipatory decision-making practices. Equally, because sampling and culturing operates at the level of farm surveillance and not in the context of responding to a specific instance of animal illness, this side tracks the temporal limitations that prevent microbial culturing being useful for diagnosis.

To be clear, this is not about backgrounding farmers and veterinary knowledge-practices in favour of microbiological knowledge. Rather, it recognises the need and capacity of farmers and vets to expand their associations with different knowledges generated by alternative technologies of 'seeing' for the benefit of animal health. Neither does this require new types of behaviour. Our empirical analysis shows that farmers and vets already synthesise knowledges, from the milking robots and microbial knowledge of resistance 'at large', respectively. Microbiological knowledge produced at the specific site of the farm (i.e., rather than 'at large') does not diminish or substitute for these knowledge-practices, but rather has the potential to enhance them and inform antibiotic choices before and during treatment.

Conclusion

At the beginning of this article we noted that knowledge claims regarding the lack of resistant animal disease encounters on farms had taken a prominent position in the public and policy debate. This contrasts with other government policy pertaining to animal health, such as biosecurity initiatives, where particularly farmers' knowledge has been largely marginalised (Enticott et al., 2012). In response to this marginalisation, scholars have traditionally interrogated the production of on-farm knowledge, what farmers know and how, as a means of highlighting both the value of local farm knowledge and the limitations of policy assumptions about animal health. However, emerging social science literature has begun to emphasise how knowledge-practices foster not only the production of knowledge but also the production and maintenance of ignorance (Bonneuil et al., 2014; Kleinman and Suryanarayanan, 2012; Murphy, 2013). Consequently, our interrogation of the claim that resistance is largely unencountered on farms advances current literature on farm knowledge-practices through explicit consideration of the boundaries of knowledge production, and the implication for understanding certain phenomena, in this case antimicrobial resistance when it falls outside of the domain of perception.

Our analysis has highlighted that there is a need to recognise the limitations of current on-farm knowledge-practices and surveillance regimes for assessing the prevalence of antimicrobial resistance in farming. Despite being adept at identifying and diagnosing ill animals, resistance is imperceptible to farmer and veterinary experiential knowledge-practices. They are ill-equipped to identify resistance when diagnosing disease due, in part, to the non-use of microbial culturing which is deemed too slow. However, when examining two sites at which resistance might be perceptible to vets and farmers, interpretations of treatment failure and herd health oversight, our analysis draws attention to a different dimension of imperception, namely, effacement. This effacement is rooted not in the imperceptibility of resistance to available knowledge-practices per se but rather the multi-faceted nature of disease and resistance as a phenomena. The multiplicity of disease and antibiotic resistance provides an alternative explanatory repertoire for understanding treatment failure. This finding emphasises the role of the phenomena itself in the production of ignorance and thus its contingency on human and non-human agencies.

Finally, this effacement and imperceptibility of resistance at the farm-level has consequences beyond any one farm. This is because it is further embedded within a passive national surveillance regime which relies on farm-level actors, particularly vets, to submit samples of suspected resistant infections. Our analysis therefore suggests that this current surveillance regime is potentially inadequate and identifies a need to establish an active farm-based surveillance regime. Equally, if the knowledge it produces is responsive to the needs of practitioners and can be usefully synthesised within on-farm decision making, particularly the practices of anticipation demonstrated by vets, then there is potential to re-shape the boundaries of what is known about antimicrobial resistant infections on farms.

Data availability

The datasets generated and analysed during the current study will be made publicly available by deposition into NERC's Environmental Information Data Centre EIDC no later than December 2019. Until such time they are available from the corresponding author on reasonable request.

Received: 28 May 2018 Accepted: 7 January 2019
Published online: 05 February 2019

Notes

1 The exception that is usually recognised is that of resistance to anthelmintics prescribed to treat infection by parasites, notably, liver fluke in sheep. While we acknowledge the importance of this aspect of AMR, we limit our analysis to resistance to antibiotics.
2 *Escherichia. coli, Streptococcus. uberis, Staphylococcus. aureus* and *Streptococcus. Dysgalactiae*, all of which are animal and human pathogens.
3 Mastitis is an infection of the mammary glands and tissues. It is endemic in dairy cattle. Key mastitis bacterial pathogens surveyed include *Escherichia. coli, Streptococcus. uberis, Staphylococcus. aureus* and *Streptococcus. Dysgalactiae*, all of which are animal and human pathogens.
4 Pregnant animals that are within the rest period before giving birth.
5 For example, average herd size in England has risen from 77 in 1997 to 150 in 2017 (ADHB Dairy, 2018)
6 TD refers to Tetra Delta an intermammary antibiotic treatment used on the farm for mastitis.
7 Nuflur is an injectable antibiotic treatment used on the farm for pneumonia in calves.
8 The milk contract with a major retailer stipulated that certain antibiotic classes could not be used on the farm.

References

ADHB Dairy (2018) Average herd size. http://dairy.ahdb.org.uk/resources-library/market-information/farming-data/average-herd-size/#.W_Kn9-j7SUk. Accessed Nov 2018

AHDB Dairy (2016) Dairy statistics: an insiders guide. AHDB Dairy, Kenilworth: UK

Anderson B (2010) Preemption, precaution, preparedness: anticipatory action and future geographies. Progress Human Geogr 34(6):777–798

Bonneuil C, Foyer J, Wynne B (2014) Genetic fallout in bio-cultural landscapes: molecular imperialism and the cultural politics of (not) seeing transgenes in Mexico. Social Stud Sci 44(6):901–929

British Veterinary Association (2015) Vets respond to Jim O'Neill report calling for phased reduction of global antibiotic use in livestock. British Veterinary Association, London

Bud R (2007) Penicillin: truimph and tragedy. Oxford University Press, Oxford

Buller H et al. (2015) Systematic review and social research to further understanding of current practice in the context of using antimicrobials in livestock farming and to inform appropriate interventions to reduce antimicrobial resistance within the livestock sector. Department of Environment, Food and Rural Affairs, London

Burgess J, Clark J, Harrison C (2000) Knowledges in action: an actor network analysis of a wetland agri-environment scheme. Ecol Econ 35:119–132

Burton R, Peoples S, Cooper M (2012) Building 'cowshed cultures': a cultural perspective on the promotion of stockmanship and animal welfare on dairy farms. J Rural Stud 28:174–187

Cannon G (1995) Superbug. Nature's revenge. Virgin Publishing, London

Clark A, Emmel N (2010) Using walking interviewsL Realities Toolkit #13. ESRC National Centre for Research Methods, UK

DEFRA & Rural Payments Agency (2012) Dairy farming and schemes: guidance. DEFRA & Rural Payments Agency, London

DoH & DEFRA (2013) UK 5 year antimicrobial resistance strategy: 2013–2018. Department of Health, London

DoH (2011) Annual report of the chief medical officer, volume two: Infections and the rise of antimicrobial. Department of Health, London

Driver A (2016) Government setting 'unachievable' targets for antibiotic use across livestock sectors. Farmers Guardian, Preston

Eden S (2008) Being fieldworthy: environmental knowledge practices and the space of the field in forest certification. Environ Plan A 26:1018–1035

Enticott G (2008) The spaces of biosecurity: prescribing and negotiating solutions to bovine tuberculosis. Environ Plan A Econ Space 40(7):1568–1582

Enticott G, Franklin A, Van Winden S (2012) Biosecurity and food security: spatial strategies for combating bovine tuberculosis in the UK. Geogr J 178 (4):327–337

European Commission (2017) Welfare of cattle on dairy farms: overview report. Publications Office of the European Union, Luxembourg

European Grassland Federation (2014) The future of grazing: livestock research report. European Grassland Federation, Wageningen UR, p 906

Fortané N, Keck F (2015) How biosecurity reframes animal surveillance. Rev d'anthropologie Des Connaiss 9(2):a–l

Gross M (2010) Ignorance and surprise: science, society and ecological design. The MIT Press, Cambridge, MA

Hinchliffe S, Bingham H, Allen J, Carter S (2017) Pathological lives: disease, space and biopolitics. John Wiley & Sons Ltd, Oxford, UK

Hinchliffe S, Ward K (2014) Geographies of folded life: How immunity reframes biosecurity. Geoforum 53:136–144

Holloway L, Bear C, Wilkinson K (2014) Robotic milking technologies and renegotiating situated ethical relationships on UK dairy farms. Agric Human Values 31(2):185–199

Holloway L, Morris C (2012) Contesting genetic knowledge-practices in livestock breeding: biopower, biosocial collectivities and heterogeneous resistances. Environ Plan D Soc Space 30(1):60–77

Holloway L, Wilkinson K, Butler D (2012) Robotic and information technologies in UK Dairy Farming. Department of Geography, Environment and Earth Sciences: Univeristy of Hull, Hull

Hughes A, Morris C, Seymour S (2000) Introduction. In: Hughes A, Morris C, Seymour S eds. Ethnography and rural research. The Countryside and Community Press, Cheltenham, p 1–27

Ingram J, Morris C (2008) The knowledge challenge within the transition towards sustainable soil management: an analysis of agricultural advisors in England. Land Use Policy 86:214–228

Kesuenbach M (2003) Street phenomenology: the go-along as ethnographic research tool. Ethnography 4:455–485

Kleinman D, Suryanarayanan S (2012) Dying bees and the social production of ignorance. Sci, Technol Human Values 38(4):492–517

Law J, Mol A (2011) Veterinary realities: what is foot and mouth disease? Sociol Rural 51(1):1–16

Levy S (2002) The antibiotic paradox: how the misuse of antibiotics destroys their curative powers. Perseus Publishing, Cambridge, MA

McGoey L (2007) On the will to ignorance in bureaucracy. Econ Soc 36(2):212–235

Morgan K, Murdoch J (2000) Organic vs. conventional agriculture: knowledge, power and innovation in the food chain. Geoforum 31:159–173

Morris C (2006) Negotiating the boundary between state-led and farmer approaches to knowing nature: an analysis of UK agri-environment schemes. Geoforum 37:113–127

Morris C, Helliwell R, Raman S (2016) Framing the agricultural use of antibiotics and antimicrobial resistance in UK national newspapers and the farming press. J Rural Stud 45:43–53

Morris C, Holloway L (2014) Genetics and livestock breeding in the UK: Co-constructing technologies and heterogeneous biosocial collectivities. J Rural Stud 33:150–160

Murphy M (2006) Sick building syndrome and the problem of uncertainty: environmental politics, technoscience, and women workers. Duke University Press, London

Murphy M (2013) Distributed Reproduction, Chemical Violence, and Latency. The Scholar and Feminist Online 11(3):1–2

O'Neill (2016) Tackling drug-resistant infections globally: final report and recommendations. HM Government, London

Proctor A, Donaldson A, Phillipson J, Lowe P (2012) Field expertise in rural land management. Environ Plan A 44:1696–1711

Proctor R, Schiebinger L (2008) Agnotology: the making and unmaking of ignorance. Stanford University Press, Stanford

Riley M (2008) Experts in their fields: farmer-expert knowleges and environmentally friendly farming practices. Environ Plan A 40:1277–1293

RUMA (2014) Information note on antibiotic resistance and the responsible use of antibiotics in farm animals. Responsible Use of Medicines in Agriculture Alliance, London

Science and Technology Committee (Commons) (2014) Oral evidence: antimicrobial resistance, HC 848, Wednesday 29 January 2014. House of Commons, London

Tsouvalis J, Seymour S, Watkins C (2000) Exploring knowledge-cultures: precision farming, yield mapping, and the expert—farmer interface. Environ Plan A 32:909–924

VMD (2017a) UK—Veterinary antibiotic resistance and sales surveillance report. Veterinary Medicines Directorate, Addlestone

VMD (2017b) UK—veterinary antibiotic resistance and sales surveillance report: supplementary material. Veterinary Medicines Directorate, London

WHO (2015) Global action plan on antimicrobial resistance. World Health Organisation, Geneva

Wynne B (1996) May the sheep safely graze? A reflexive view of the expert-lay knowledge divide. In: Lash S, Szerszynski B, Wynne B eds. Risk, environment and modernity: towards a new ecology. SAGE, London, p 44–83

Acknowledgements

This work was supported by the Natural Environment Research Council [grant number NE/N01M9881/1].

Additional information

Competing interests: The authors declare no competing interests.