Regulating antimicrobial resistance

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Regulating antimicrobial resistance: market intermediaries, poultry and the audit lock-in

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Abstract
Antimicrobial resistance (AMR) has become one of the defining challenges of the twenty-first century. Food production and farming are a key if troubling component of that challenge. Livestock production accounts for well over half of annual global consumption of antimicrobials, though the contribution of the sector to drug resistance is less clear. As a result, there is an injunction to act in advance of incontrovertible evidence for change. In this paper we engage with the role of market actors in the precautionary regulation of farming practices and AMR threats. The paper takes the UK poultry sector as exemplary of an audit-led process that has, in recent years, achieved impressive reductions in antimicrobial use. Using qualitative interview data with farmers and veterinarians we chart the changing practices that have accompanied this reduction in treatments. We use this analysis to raise some cautions around audit-led systems of regulation. Audits can lock farms and animals into particular versions of farming and animal health; they can elevate harmful compensatory practices (including disinfectant uses); and they can reproduce an actuarial approach to an issue that does not fit the conventions of risk management. The paper presents the considerable successes that have been achieved over a short period of time in a livestock sector, while generating notes of caution concerning the audit-led management of livestock-related AMR threats.

Keywords Antimicrobial resistance · Farming · Audit · Regulation · Social science

Introduction

The emergence, persistence and transmission of microorganisms that can withstand existing treatments and medicines have made antimicrobial resistance (AMR) a key concern for human and animal health as well as for food and environmental security (Laxminarayan et al. 2013). AMR refers to a range of effects wherein previously treatable infections are no longer responsive to available medicines (in vivo); where laboratory cultures are no longer susceptible to formerly inhibitory concentrations of antimicrobial compounds (in vitro); and/or where characteristic genetic materials are identified within microorganisms that can confer or transmit resistance traits (Chandler 2019). AMR is frequently referred to as a silent or slow pandemic (Mahoney et al. 2021), indicating the progressive and extensive increase in associated and attributed deaths from resistant microbes. Untreatable infections have increased in many parts of the world, particularly in areas where there are high levels of poverty and poor infection prevention (Murray et al. 2022). Escalating AMR is generally considered to be associated with the mass production and widespread use of antibiotics and other antimicrobial compounds.[1] Industrial-scale production, associated pollution, and liberal use of antimicrobials have altered evolutionary selection pressures and resulted in global changes to microbial cell processes (Gillings 2017;

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[1] Antibiotics refers to natural and synthesized compounds that target bacteria. Antimicrobials is a more general term to refer to antibiotics and to other compounds that may target viruses, fungi and protozoa. Where appropriate we use the more general term—antimicrobial—as this is implied in AMR, though it is worth noting that most antimicrobials used in livestock farming are antibiotics.

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Landecker 2016). Demand for antimicrobial products has grown in the last half century, driven by, and contributing to, a variety of social changes that include dense urban living, centralised and busy health care systems, and expanded food production. Antimicrobial use is often cost-efficient at the point of use, and has become an infrastructural component of health systems and a crutch for economic production and precarious lifestyles (Denyer Willis and Chandler 2019; Roope et al. 2019; Hinchliffe et al. 2018). Many food and farming systems have also become reliant on antimicrobial use to control infection and to promote production (Kirchhelle 2020). Concerns around the continued and sustained effectiveness of treatments have been simultaneously compounded by a near collapse of pharmaceutical antimicrobial innovation and drug development (World Health Organisation 2022). If antimicrobials once offered the means to control the ever-present threat of debilitating infections, drug resistance has, as Landecker (2016: 44) noted, initiated "a strange time of controlling the prior means of control".

In this general landscape of concern over resistance threats, food and farming play a significant, if contested, role. Livestock farming accounts for more than half of annual global antimicrobial consumption (Van Boeckel et al. 2014). Usage in cattle, pig and poultry production can be particularly pronounced, though can vary widely in those production systems (Van Boeckel et al. 2015). The consequences of this use for human, animal and environmental health are less easily determined. Antimicrobial use in farmed animals is likely to increase emergence, persistence and transmission of resistant microbes and genes. There is evidence of transfer of resistant microbes to livestock workers in pig production in Denmark (Borck Høg et al. 2017), inferred associations between bacterial strains in livestock and human infections (Liu et al. 2023), as well as evidence that reduced antimicrobial use in food production settings is associated with fewer resistant bacteria in human-derived clinical samples (Casey et al. 2023). Some reviews, however, suggest that livestock-to-human transmission may be relatively uncommon (Zou et al. 2022) and raise questions over the directionality of transfers (Muloi et al. 2018). Evidence remains relatively limited, with estimates of disease and resistance burdens based on clinical data rather than active surveillance of community, animal health or environmental resistance markers (Fortané 2021). While the threat of livestock-related resistance events is strongly implied, and a large proportion of antimicrobial use in farming and food production is considered to be avoidable, in legal terms the burden of responsibility is in advance of incontrovertible evidence of clear linkages between antimicrobial uses in food production and public, animal and environmental health consequences.

The resulting regulatory situation is marked by high stakes and large scientific uncertainties. The probabilities of zoonotic transfer of resistance conferring microbes or genes may be difficult to quantify owing to several epistemic uncertainties (difficulties of measurement, a failure to agree on the key objects for attention, complex pathways, phenotypical and ecological differences in microorganism behaviours, as well as the intrinsic uncertainties that relate to evolutionary processes). The associated difficulties in terms of risk calculability and object stabilisation contributed to what Chandler (2019), following Lakoff (2015), characterised as a sentinel rather than actuarial approach to the AMR issue. Whereas actuarial approaches utilise relatively robust historical and scientific data to furnish the assessment and prevention of risks (Stirling 2010), sentinel objects are often data poor, with reduced certainty regarding outcomes and probabilities. As a result, risk management tends towards more speculative and precautionary forms of regulative action (Amoore 2013; Anderson 2010; Cooper 2006). The uncertainties of post-colony microbial sciences, in which monogenomic cell lines have been displaced by promiscuous communities of living entities who share genetic traits (Hinchliffe 2021), and the rise of neoliberal and market-led forms of regulation, add emphasis to this shift in the objects and means of control. As a result, AMR has been characterised by speculative economic assessment, voluntary behaviour change programmes, the championing of exemplary actions and data surveillance measures rather than an explicit interdiction or more interventionist programmes of action (Chandler 2019).

In practice, actuarial and sentinel approaches are likely to be found side-by-side as established routines and procedures re-orient to new threats and realignments of states and markets. It is this mix of regulatory styles and objects that require empirical investigation. This is particularly apposite in health care settings and, in higher income countries, food and farming sectors, both of which are increasingly characterised by record keeping, datafication and auditing systems (Griffiths et al. 2017; Freidberg 2017). In these settings, disease diagnoses, health histories and treatments are recorded, attached to and circulate with patients or produce, and are collated centrally in ways that allow for the monitoring and future shaping of prescriber and sector performance. As such, audit processes are utilised to enable particular forms of organisational governance (Miller and Rose 1990; Power 1997; Miller 1998) and to manage reputational risks (Power 2007; Power et al. 2009). In food production, such systems have become core activities for retailers and processors with complex value chains and supply networks. They enable sector-wide oversight, and provide assurance on matters of food safety, welfare standards and environmental performance (Marsden et al. 2009; Hinchliffe et al. 2016; Escobar and Demeritt 2017; Hughes et al. 2021). These systems are advanced by a proliferation of devices (diagnostic tools, monitoring systems, and data-systems) that open new possibilities and problems for data-driven changes (Freidberg 2017, 2020).

In this paper, we focus on the UK's poultry sector as exemplary of industry-led approaches to antimicrobial usage reduction (FAO and VMD 2022). We demonstrate how an audit-style approach to sector governance has been applied to a sentinel problem, through a market intermediary-led programme that facilitated precautionary action on AMR. We use interviews with farmers, farm owners and veterinarians, to discuss the implications of, and potential limitations to, this form of regulation. We start by briefly summarising the history of poultry—and particularly chicken—production, its historical reliance on antimicrobials, its structure and regulation and the development of industry-led approaches to antimicrobial stewardship. After discussing our methodology, we develop a thematic analysis of interviews, focusing on the consequences of audit-led regulation on farm practices, disease diagnoses and animal health. We conclude with an assessment of those consequences and discuss the concept of audit lock-in (when the means of producing change perpetuate practices that contribute to the situation at hand) in relation to the particular framings of health that are generated in audit systems.

Regulating chicken—reducing antimicrobial uses and the role of market intermediaries

Following the depression-era promise of 'putting a chicken in every pot' (Smith and Daniel 1982), Charles Vantress's prized hybrid breeds, and faster growing 'Chicken of Tomorrow' (McKenna 2017), poultry farming evolved from the mid-twentieth century to become an industrial-scale global enterprise (Godley and Williams 2008, 2009). Boyd and Watts (1997) described broiler chicken as a bundle of socio-technical relations involving re-orientations of human labour, industrial agglomeration and integration, technical shifts in farming practice, value chain management and retailer expansion. Animal breeding, feed additives, improved housing, and the liberal use of antibiotics to secure and promote rapid growth at volume and density within increasingly tight economic margins in integrated systems of production, generated a form of food that has become the dominant source of animal-related protein in global diets. Global poultry meat production reached 137 M tonnes per annum in 2020 and is expected to reach 166 M tonnes by 2030, with per capita annual consumption around 60 kg in the US, Malaysia and Brazil (Global Poultry Market Report 2021). Poultry makes up roughly half of all meat consumption in the UK, and the UK alone consumes over 13.5 billion eggs a year (37 M per day), with over 90% domestically produced (British Lion Eggs 2022). Production is high volume with low margins for growers, processors and retailers (Allen and Lavau 2014). The majority of poultry meat production in the UK is vertically integrated, with large supermarket chains specifying contracts with processors who organise all aspects of grow out (through contracts with farmers, and/ or ownership or management of farms) (Godley and Williams 2008). Poultry farms are contracted to produce specific numbers of birds at set price points, by set dates, taking delivery of day-old chicks, feed rations and other inputs. Farmers provide and/ or manage the buildings and work to comply with the stipulations and regulations set down by retailers, via a processor company. Major retailers market produce as quality assured, utilising the UK's Red Tractor Assurance (RTA) scheme as an industry standard (RTA was initiated in 2000). The latter specifies a wide variety of production standards (revised periodically) that include animal welfare measures, staff training, housing, diet and biosecurity. In 2016, RTA tightened antimicrobial usage stipulations, specifying that "antibiotics can only ever be used for specific treatment of disease, and only under the direction of a vet where a formal diagnosis has been made. All antibiotic usage is recorded and reported" (Red Tractor Farm Assurance 2023). Industry structure for layers is, by comparison, less integrated, though most producers sell to market intermediaries, and retailer standards are organised through the British Egg Industry Council (BEIC) who operate the Lion Code on their assured produce. All antibiotic uses are required to be reported to BEIC on a quarterly basis. In both cases, assurance schemes pass antimicrobial use data to the UK Government's Veterinary Medicines Directorate (VMD) to enable collation and annual reporting. Within this broad description of production, it is worthy of note that in the UK there is a considerable variability across the poultry sector, with well-established welfare-assured, free range and organic production styles reflecting a moral economy (Jackson et al. 2009) of 'qualified' produce and markets (Callon 1998), underpinned by advances in traceability (Donaldson 2021).

The history of antimicrobial regulation in poultry production has been chronicled in the UK context by Kirchhelle (Kirchhelle 2018a, 2020), highlighting lost opportunities to intervene in the industry, particularly following the 1965 outbreak of antibiotic-resistant salmonella and the resulting Swann Inquiry. While antibiotic-related growth promoters were subsequently banned in the UK in 1971, there was no action in terms of limiting prophylactic or metaphylactic uses (dosing an entire flock in anticipation of an infection), effectively sanctioning ongoing liberal use of antimicrobials in livestock farming. In Kirchhelle's (2018b) analysis, further regulation was impeded by fears over the effects on the rural economy, on international competitiveness and the loss of earnings from veterinary sales. Use of antimicrobials for livestock growth promotion was banned in the EU in 2006, though implementation was uneven across the continent and grey areas concerning treatments remained. McKenna (2017) charted similar territory in the US, with post-slaughter carcass antimicrobial treatments resulting in early evidence of the spread of resistant microbes from poultry to factory workers and consumers. There, the regulatory process was even more constrained by the early concentration of socio-economic power within a handful of large, vertically integrated companies, and growth promotion remains legal in many states.

By the 2010s, several factors contributed to something of a turning point and an extension of industry-led action on antimicrobial use in livestock. In the UK, an important development came with the UK's Chief Medical Officer Dame Sally Davis's (2013) championing of the issue, a UK Cabinet Office-backed review and two UK government reports (The Review on Antimicrobial Resistance, 2014; The Review on Antimicrobial Resistance, 2016). As Hughes et al. (2021: p. 1374) noted, these reports—which covered human as well as animal health—"positioned supermarket chains, processors and regulators as a set of influential actors beyond the healthcare setting with responsibilities for attending to AMR in the food system." Food sector actors, including veterinarians, farmers, assurance schemes, trade associations and lobby groups, were faced with the collective problem of reducing "the extensive and unnecessary use of antibiotics in agriculture" (The Review on Antimicrobial Resistance, 2015: p. 2). While the injunction initially caused some consternation that the sector was being blamed for a human health-derived problem, treatment reductions were increasingly understood as achievable, timely, in-train (especially in neighbouring states, including the Netherlands, which had set tough laws on use in 2011), and something that a sector marked by a form of retailer-led governance would need to enact. The UK's broiler industry trade council had already set up an antimicrobial stewardship scheme in 2011, and there was a clear will to be seen to be acting responsibly.

For some commentators, public concern was a key driver of change: "Media interest was increasingly focused on the links between use of antibiotics in animals and development of resistance in humans, despite limited scientific evidence being available. (…) In addition, pressure was applied by lobby groups and non-governmental organizations campaigning for changes in farming practices. This attention led to increased public awareness of the issue, and in response to consumer demand, retailers also began questioning the farmers supplying their stores about use of antibiotics in the animals they farmed" (FAO and VMD 2022: p. 6). While the level of public awareness may be overstated (Wellcome Trust 2019; Will 2019), potential reputational risks for retailers associated with antimicrobial uses are clearly implied. The poultry industry were also keen to generate farm usage data to overcome the problem of being grouped together with the pig sector in antimicrobial sales data. Differentiating the sector from pigs would potentially reduce risks of future regulation. The threat of new legislation, including draft European Union veterinary medicine regulation in 2014 which would insist on antimicrobial use data, focused industry attention (FAO and VMD 2022). The UK political context favoured a voluntary, market-led approach, pushing compliance into organisations rather than seeking external forms of control (Power 1997), while industry were keen to act on their own terms and conditions. As one leading industry representative stated, "Once you put legislation in place, you can create a lot of barriers and problems […] Our approach was to work with the government and demonstrate that these products were being used responsibly" (Davies 2019: np). Government departments, working at low capacity with little ministerial support for more red tape, were happy to task the industry with responding pro-actively and to self-govern (FAO and VMD 2022).

Brand-aware retailers, and processors keen to maintain contracts with those chains, worked with trade associations (British Poultry Council, BEIC) as well as state-based (VMD) and non-profit cross sector bodies (RUMA—Responsible Use of Medicines in Agriculture Alliance, an association of supply and value chain actors) to set industry targets and encourage change. The resulting targets and data gathering procedures allowed these established as well as newly constituted market intermediaries to act *in place of* consumers of poultry farm produce, stipulating the amounts and acceptable conditions for antimicrobial use. These market intermediaries were, in that sense, close to what Miller (2012) termed virtual consumers—a group of actors who displace actual consumers in a market, representing a yet to be realised 'public' (Miller 1998). In this economic virtualism (which has nothing directly to do with virtual or digital realms), market intermediaries utilise market devices including audits, assurance schemes and other techniques to alter the field of consumption.

In our reading, a dual aspect of virtual consumers (acting on behalf of as well as in advance of a fully articulated public) has the advantage of being able to respond to potential rather than actual threats to future market activity. Change is driven by a need to maintain brand confidence, manage reputational risk, develop brand differentiation and by the anticipation of being held to account by a public or public institution at some future date (better to reduce antimicrobial use now than wait for future enquiries or actions that may deem any failure to act as negligent) (Ewald 1993). On the positive side, this anticipatory logic befits a precautionary, or less empirical (evidential), form of regulation. Virtual consumers can protect public health or other shared goals even in the absence of scientific proof for legal interdiction. Nevertheless, as is commonly understood, the associated audit culture can produce notable and sometimes perverse effects on public policy or market activity (Strathern 2000). They can suffer from poor levels of compliance, or a decoupling of policy and practice. Or, rules and policies are implemented but with uncertain relation to the desirable outcomes, with the result that means and ends are decoupled (Bromley and Powell 2012). For example, reductions of antimicrobial use per unit of produce may divert attention from expansion of overall output and from other conditions or factors that may contribute to the AMR threat. Our engagement with market intermediaries as virtual consumers in the context of regulating livestock production keeps these precautionary, distortive and decoupling effects in play.

Resulting action on antimicrobial use in the broiler sector was coordinated by the British Poultry Council (BPC), a trade association for those involved in the production of poultry meat, and BEIC for layers. The results were impressive, with a reported reduction of antibiotic use of 82% in broilers over the initial five-year period (2012–2017) (British Poultry Council 2021) and around 30% in layers after 2016. The common unit used to make comparisons from the 2011 baseline was mg/PCU (population correction unit) which effectively estimates the amount of antimicrobial used in each kilogramme of produce. BPC also reported total tonnage of antimicrobials used in the sector. There were some initial concerns that these figures were masking treatment substitution effects (replacing low potency antimicrobial treatments with lower volumes of more powerful medicines). For example, use of fluoroquinolones (a family of critically important antibiotics—CIAs) increased by 59% in 2013–2014. The concerns were short-lived, and, by 2021, the BPC reported a 97.2% reduction in fluoroquinolone use and a 95.5% reduction in the use of CIAs compared to the 2011 baseline (British Poultry Council 2021). Nevertheless, this fear concerning displacement signalled a wider audit issue—the monitoring of antimicrobial use through average dosage amounts per animal and through tonnage across sectors was a useful proxy for AMR risk, but could miss the ecological complexities of the issue. For example, antimicrobials vary in terms of their potency, their effects on specific bacterial types, and their bioavailability and resistance related effects can vary widely in terms of the animals treated and their environmental conditions (EUCAST 2003). Some of these concerns could be allayed by the relatively small range of permitted antimicrobial products licensed for use in food animals in the UK (including a Red Tractor ban on third and fourth generation Cephalosporins in 2012 and Colistin in 2016). Even so, the impressive figures used by the industry to demonstrate successful stewardship across the sector in this period remained a proxy for, rather than definitive proof of, a diminished resistance problem.

It is worthy of note that a portion of the initial reduction in treatment usages was the result of sector-wide changes that had little direct relation to antimicrobial stewardship. The conversion of poultry house heating to external biomass boilers (encouraged through government schemes aiming to move to renewable rural heating) reduced moisture and condensation problems in houses, improving litter quality and the gut health of the birds (Davies 2019). Other gains were, as we will show, related to the role of market intermediaries, audit and the importance of diagnostics and measurement practices. Further and sustained reductions in antimicrobial use in farming were frequently reported as conditional on improved diagnostic precision (The Review on Antimicrobial Resistance, 2014; The Review on Antimicrobial Resistance, 2015; The Review on Antimicrobial Resistance, 2016; Buller et al. 2020). It is these investments in metrology and diagnostics, and their relation to the auditing and governing of on-farm practices through market intermediaries, to which we now turn. Our purpose is to identify the key mechanisms for and implications of recent changes to treatment and animal health-related practices on the farm. Our concern is how the sector was changing in response to virtual consumer-led stewardship schemes, how these 'touched down' in terms of changing practices in barns and poultry houses, and how we might assess future directions of travel.

Methodology and materials

Within an overall data set including 60 interviews across livestock sectors, several focus group discussions, and a survey of British veterinarians on diagnostic practices in farming, the main materials used for this paper involve long, semi-structured interviews with veterinarians with specialist expertise in the poultry sector (n = 10) and with poultry farmers (n = 10). All interviews were conducted in 2020 and 2021. Veterinarians were recruited purposively through industry experts and contacts. These veterinarians covered large parts of the commercial poultry sector in the UK. Poultry veterinarians tended to be specialist, dealing mainly or solely with poultry farms. They worked for large practices or consultancies and were contracted to corporate processors who either owned or sub-contracted to multiple farms. The purposive sample of poultry farmers covered a range of production types and supply chain characteristics (Table 1). Interviewees were recruited from across GB poultry (England, Wales, Scotland), though were mainly based in England. All except one of the veterinary interviews were face-to-face, while all but one of the farmer interviews took place via video call. All interviews involved a veterinary scientist and a social scientist as co-interviewers (enabling informed follow-up questions in line with disciplinary expertise). The interviews were semi-structured conversations (McCracken 1988), lasting between one and two hours, and allowed interviewees to drive topics and develop themes. The list of interview topics was decided by a multi-disciplinary team

Table 1 Participant farmers or farm managers

Identifier	Main produce	Brief characteristic of farm/s and supply chain
PF 1	Standard broiler	Large (300 k + birds)—supply major processor
PF 2	Standard broiler	Large (300 k + birds)—supply major processor
PF 3	Standard broiler	Large (300 k + birds), multiple farms—supply major processor
PF 4	Free range layer	Medium (24 k birds)—contract to major supplier to retailers
PF 5	Free range organic layer	Medium (12 k birds)—supplies major supermarket
PF 6	Free range organic layer	Medium (12 k birds)—contract to major free-range and organic supplier
PF 7	Free range layer	Medium (16 k birds)—ex-contract to major supplier, now supply local small company
PF 8	Organic pullet rearing	Medium (40 k birds)—supply to layer industry
PF 9	Broiler breeders, 2 sites	Medium (74 k birds)—supply chicks to standard grow-out farms
PF 10	Standard broiler	Medium–large (128 k birds)—supply integrated processor

and ranged from describing participants' working lives and their daily activities to key animal health concerns, events or experiences, diagnostic practices and uses of treatments (with a special focus on antimicrobials). A focus group with poultry veterinarians was conducted in 2022 with an emphasis on the future of diagnostic practices, particularly with respect to automated monitoring and data use in the industry. While the purpose of this research was to develop analytical and explanatory depth rather than industry-wide breadth (Sayer 1992), it is nevertheless worthy of note that poultry industry practices are relatively standardised and that people working within the specialised sector often have a breadth of knowledge beyond individual veterinary practices or farms. In this sense, the interviews and focus group offered a rich resource of experience and knowledge of animal health care, farming practices and industry norms.

All interviews and focus groups were recorded, transcribed and analysed by the team. Initial coding schemes were derived through a deliberative process of reading transcripts and deriving codes through an agreed format of context, materials and outcomes. For example, context in the poultry sector included temporalities (speed of production) and the high levels of integration of the sector; materials included housing, the importance of litter and the taking of blood samples for serology; outcomes included treatment decisions or changes to production processes, loss of productivity, sales and so on. To improve analytical consistency across the corpus of transcripts (which included work in other livestock sectors—pigs and dairy cattle), once all transcripts had been read and coding ideas compared, the team agreed an initial, high-level coding scheme. At least two members of the research team were involved in reading and discussing each transcript and its subsequent coding. Work was shared using the *NVivo* team working function. Individual members of the team developed more detailed sub-coding and thematic summaries of the corpus of data and subsequently generated further analysis of materials through development of cross-code searches of the data and in-depth as well in-context engagement with emergent themes. This second analytical stage involved an explanatory focus, highlighting discursive repertoires (the ways in which health or other topics were framed or talked about and enacted or practised). Examples included the use of terms like 'system' to facilitate discussion of high mortality or culling of animals, or good and bad birds to justify the sorting and culling of animals. This analytical structure (starting with core project themes followed by identification and analysis of repertoires and speech) was chosen as a pragmatic solution to interdisciplinary team-based research allowing for sharing of data themes prior to more detailed investigations.

All the vets were based at large commercial poultry practices or poultry consultancies in England or Scotland. As the total number of poultry veterinarians in the UK is small, and as our sample covers large parts of a highly integrated and standardised sector, for simplicity, and to protect anonymity, we refer to all poultry veterinarians as PV.

Results

The following themes were developed from the analysis of empirical materials: changing farming practices, diagnosing disease and codifying health. We discuss each in turn.

Changing farm practices

Poultry meat and egg production are flock-based enterprises. Animal health is organised via the 'house' and the production system. Prior to investment in stewardship and assurance scheme audits in 2011 and then Red Tractor adopting new antimicrobial standards in 2016, exisiting or anticipated stock problems would be managed though routine group treatment with antimicrobials. As this farmer recalls:

> "We just used the antibiotics for the first three days. It was almost like an industry-wide insurance policy because if they [the birds] get ill in the first few days they're never that good again… So, we all blanket-medicated…" (PF10).

The practicalities of farming at volume, at density, with high transmission risks and low margins, necessitated this prophylactic and pragmatic approach to disease and health.

> "On the scale of farming nowadays, certainly on poultry, if you have 45 or 50 thousand broilers in a shed, how do you pick out the worst 20% that actually need the antibiotic without treating the whole shed?" (PF9).

Indeed, prior to antimicrobial audits, this statistical inevitability of finding a few ill birds in a shed of thousands, as well as the infectability of the flock, was justification for pro- and meta-phylaxis, or the dosing of an entire house to treat anticipated or actual infections prior to their becoming a flock-wide problem. As the farmers went on to discuss, these 'blanket' responses to disease risks became more difficult to implement once pressure was exerted from those further up the value chain ('they' in the following extract).

> "We all blanket-medicated and they kept saying, 'You've got to stop, you've to stop'. In the end I was told, 'Right, that's it, you've got to stop now; Red Tractor will not allow it anymore'" (PF10).

Stopping blanket medication meant that farmers would need to remove birds that posed a risk to the crop and to economic margins (those birds that wouldn't 'get to weight'), and, as we will detail later, invest in different approaches to flock health. "Instead of just masking a problem with an antibiotic, we're now having to deal with that problem in other ways" (PF2). As the farmers saw it, the 'problem' would often refer to the arrival of 'substandard' birds onto the farm from the hatcheries and breeders. Without the quick fix of treatments, the next option was to cull. As one farmer put it, "Where there's livestock, there's dead stock" (PF9). Indeed, farmers and veterinarians invoked a 'system', the success of which involved the sorting of birds into the 'good' and the 'bad' (stock that was to be culled). This lack of sentimentality aside, the difficulty was getting this process right and making sure that increased mortality figures did not themselves trigger public concern or attention from retailers. The trade-off between production and welfare generated some tensions (even 'battles') between the guidance issued by virtual consumers (retailers, assurance schemes and so on, with a compulsion to reduce treatments as well as keep mortality figures reasonable), the advice of veterinarians (with a professional ethos to reduce suffering) and the farmer (concerned about flock condition, maintaining contracts with buyers, and delivering their crop at a specific price point). As this farmer described it:

> "We still can use antibiotics and there's no… providing we've got the justification and the need then we can, but it's getting to that point where you say, 'Right, this is… these birds aren't right, it's becoming a welfare issue, if you like, to not intervene,' and that's the battle because you've maybe in some circumstances got the vet saying, 'Well, treat them,' but then you've got your processors saying, 'Well, we'd prefer it if you don't treat them because we then have to justify why those levels…' because obviously every crop we have to do a mg/PCU of active ingredient, so then the processor has to justify to the retailer why that batch of chickens has got that figure against it, and that's the thing with traceability, and it needs to be, so that's the conflict really" (PF2).

If the pre-audit treatment regimen involved a broad consensus across all actors within the value chain (largely based on cost efficiencies of blanket medication), the audit-led situation involved negotiation over multiple 'goods' (animal welfare, profit, treatment figures) and actors (farmers, birds, veterinarians, virtual consumers). Nevertheless, the power of audit was clear—farm businesses were made to account for treatments as part of the terms of their contracts to produce and supply. The result was a downward pressure on those practices. Moreover, any decision to utilise treatments would require justificatory diagnostic information, reports on the suitability of those treatments (or the antimicrobial sensitivities of sampled microorganisms), accompanied by documentation of the dates and amounts of treatment administered. The farmer accepted 'the need' for this traceability of both food produce and on-farm practices. Assembling and presenting data had become a normal and normalising part of farming practice.

> "[Following a veterinary intervention] a couple of days later I'll get the post-mortem report. It will come as an email and all the sensitivity reports and all that. They have a computer system where it's all logged for you, a thing called [brand name of data management system] and all the medications, everything that they do is all listed on that, which is great when you do your Red Tractor audit. You just show everything!" (PF10)

Market intermediaries relied on this version of transparency (showing "everything" meant the assembled records) to collate annual reports and demonstrate business and farming trends. A key issue for our purposes is the way in which this audit process started to re-shape farming and animal health care practices. Removing routine treatments involved developing compensatory practices to offset medicine withdrawal. Some of these involved greater attention to animal health (see later), but there was a risk that those matters that were incorporated and audited as flock qualities (antimicrobial uses) were managed downwards while other inputs (some of which might be potentially dangerous to public health, and could be co-selectors of resistance), which were not audited, increased. Disinfectants (some with carcinogenic properties) and ionophores (antimicrobials used to treat coccidiosis and classified as feed additives rather than veterinary medicines), for example, were used to compensate for restricted antibiotic treatments:

> "We went through a really, really bad time with chickens. We just could not get the weight on them so then we weren't making any money. We sacked the washing contractor because they weren't doing the job properly and (…) we told [the new contractor] what products we were using and [they] said, 'Right, we want you to do it like this.' I'd stopped using formalin years ago because I hate the product—I think it's dangerous stuff—and they said, 'You need to use formalin.' The first crop they washed out and used formalin. The difference in the chicken weight and the health of the chickens was unbelievable, so we just use formalin every crop now with disinfectant. They keep saying they're going to ban it, but they never do" (PF10).

> "We've spent a lot of money on chemical—disinfectant chemicals. So, we're treating with chemicals—prescribed anti…—well, it's not an antibiotic, it's a chemical we put in through the water lines which is incredibly expensive. Disinfectant. Again, incredibly expensive disinfectant. Five times the price of normal disinfectant but will kill cocci [protozoa that attack the intestinal tract associated with coccidiosis]" (PF3).

Managing flocks without the 'insurance' of routine antimicrobial treatment involved changes to on-farm practices. Audit exerted downwards pressure on specific activities, while producing incentives to compromise other 'goods' (for example mortality rates) or increase use of compensatory practices that were not subject to audit. We now turn to the role of diagnostics in this audit-led process.

Diagnosing disease

Audit systems are in large part dependent on the circulation of numbers, including, as we have shown, treatment amounts given to livestock. Treatment numbers were accompanied by justifications, including confirmation that a treatment was appropriate (administered correctly to the right species, to the right infection, and for microorganisms that were susceptible to the prescribed antimicrobial). A key part of the audit system was to ensure that treatment decisions were accompanied by necessary meta-data showing a trail of tests and justifications for use.

In ideal situations, diagnostic confirmatory tests could provide incontrovertible evidence for a specific infection and its susceptibility to treatment, and so provide veterinarians and farmers with clear decision tools. Much of this diagnostic work was previously accomplished through an empirical process (treat with antimicrobials, and if the birds recover then the problem was likely to have been bacterial), followed, if possible, by laboratory-based confirmation. In the UK, farmers would report a problem to the veterinarians, the poultry flock would be sampled and roughly six birds would be culled and subject to post-mortem to confirm suspected diagnoses. Post-mortems and laboratory confirmation of infections were considered to be timely and useful provided that treatment wasn't delayed (in housed poultry, time is short—birds grow quickly and infection spreads rapidly). Once diagnostic confirmation became mandatory *prior to* treatment commencing, any delay in receiving test results became critical.

> "(The veterinarian is) not allowed to give us a prescription for those birds until [they've] got the results back because, like I said before, [name of supermarket] are very strict on it, so we've got to be as quick as possible getting something to [them] so [they] can get the results off, otherwise we can be almost thinking, 'Oh, no, it's only one day,' or 'It's only two days like this' and it [egg production] keeps going down and down and down and, like I say, I think we lost 40 [birds] in that week, but if you're not careful you're losing a hundred and something birds" (PF6).

Rapid and pen-side tests that provided on-site and near real-time results were one possible solution to these industry-generated audit pressures. Cutting out the necessity to wait for laboratory results was attractive, but there was a degree of scepticism regarding test accuracy and the utility of results. Existing tests were far from fool-proof, and, even when speculating on the role of future tests, participants saw test results as part of, rather than a substitute for, a multidimensional problem-solving process.

> "We never treat in isolation, it's always in context. … So, just 'cause you've got high levels of *E. coli* doesn't mean that they need treatment. We would also compare that to how the birds look on the farm, the mortality figures that have been reported, that sort of thing" (PV).

Numbers (or levels of bacteria) needed to be contextualised, and in this case veterinary experience was required to interpret test results. Drawing together farm, flock and other health indicators or histories was important, as was the specificity of the test and the likely implications or trajectory of a disease.

> "The rotavirus kits (…)—they're designed for cattle—so they detect Group A rotavirus—I believe primarily because that's the worse one in cattle (…) so if we get it, and it comes back with a positive, then it's like, 'Fantastic, they've got Rotavirus.' But if it comes back negative—Type D rotavirus is also really bad in poultry—so you can't rule out rotavirus just because you've got a negative" (PV).

This lack of specificity in terms of the diagnostic, and the severity of the associated condition, meant that false negatives would have devastating consequences. In other cases, the results of a diagnostic test could be complicated by the immune history of the flock (for example, the widespread use of vaccines or previous exposure to disease could compromise some test results), while vaccination or prior infection was seldom a guarantee that the birds would not develop infection.

> "Even a really high level of immunity can still be overcome in the face of a potentially high pathogenic challenge. Or, in the case of birds, high stresses; or, in the case of *E. coli*, extremely pathogenic *E. coli* (…) there might be an infectious bronchitis component which quite often predisposes the birds to *E. coli* deaths. So, you get this viral infection of the trachea and then *E. coli* jumps in off the back of that viral damage" (PV).

Reading a test result required context-specific as well as disease expertise. Veterinarian participants knew that tests would often be inconclusive, results could be masked by vaccine-related antibodies in certain situations, and treatment decisions would be conditional on other information over and above the presence or absence of a microbe. So, despite the definitive promise of diagnostic tests, diagnoses frequently required a rounded judgement. Auditability potentially became more complex (the meta-data around a treatment decision was more open to interpretation). Rapid tests were unlikely to provide a simple discriminator, often yielding circumstantial rather than incontrovertible evidence on questions of treatment. Presence or absence of susceptible microbes was complicated by the age of the birds, their vaccine status, their likely recovery and whether it was better to treat now rather than risk waiting for a condition to deteriorate:

> "Sometimes you have to treat sub-clinical […] levels of *Enterococcus* because it can [lead to] severe lameness later on. (…) it's not only cheaper for the client, but you're actually using a lot less antibiotics, so it's much more responsible, rather than using it when they're 2 kilos heavier, and they're less likely to respond to treatment anyway…" (PV).

Beyond the rubric of the virtual consumer-led audit—to treat only under specific circumstances—it became clear that circumstances were themselves conditional (and required professional judgement in terms of diagnoses and prognoses). It wasn't device precision per se that was needed, but an ability to read the environment and disease situation more clearly.

Codifying health

As currently available diagnostic tests rarely produced the kinds of results that could circulate independently and freely, without further qualification, the more significant outcomes of reductions in routine antibiotics were, first, the growth in attention to flock and farm health, and, second, the role of monitoring and data generation as means to codify health and allow it to circulate. Some of this adjustment marked a shift in quantities (reducing the number of birds while increasing their weight) and, less clearly, quality (with some sense that welfare and wellbeing might be improved).

> "We're carrying a lot less birds than we used to, but taking them to a heavier weight, so you could argue that we're still making the same return per metre from that; but, ultimately, I think stocking will only go down and welfare, hopefully, will only go up and I think that's… whether the bird changes and we grow less birds for longer and a more welfare friendly system, I don't know" (PF2).

This shift in production was accompanied by an understanding hat flock health was increasingly understood as a data-rich, auditable matter:

> "At the moment everything's an interpretation and a viewpoint, whereas if you've got those hi-tech monitoring systems in place, it's a far more informed decision because you know this, this and this, whereas before you wouldn't have done. Yeah, and I think in a broiler environment, that's very feasible" (PF2).

In our interviews, flock health displaced treatment as the key concern that helped to constitute the working relationship between farmers and veterinarians. Veterinarians were described by farmers as essential partners in the process of improving outcomes and in generating the kinds of authority that were needed for health information to circulate successfully.

> "I think the fact that we've gone antibiotic-free as such has meant that there's a lot more focus on making sure the health is better" (PF9).

> "[The relationship between the farm and the veterinarian is] far more interactive and far more contact than we used to have, but most of that is driven through antibiotic reduction" (PF2).

> "I very much see the vet as a member of the team. We don't just use them for firefighting" (PF3).

Veterinarians were being re-positioned as health consultants, advising on animal health and productivity rather than disease and treatments (with a shift in terms of the practice-business model). In poultry this meant dealing with queries relating to current flocks, and, increasingly, helping to plan the health of future farm bird placements. The aim was to optimise environments, to improve birds and bird inputs (vaccines and feed). "A lot of it is assessing birds and then slightly adjusting parameters" (PF1). In terms of the 'parameters':

> "It's all about getting everything right and doing everything as well as you can, just to get that peak performance because we're all given the same feed and we're all given the same chicks—well, within reason—so to give yourself competitive advantage it's basically down to attention on those birds and what you can do to them to make them more efficient, healthier, so hence the veterinary involvement in trying to drive all those little tweaks to get that extra performance" (PF2).

'Peak performance' has marked poultry production for decades, but for some farmers managing the parameters had become more salient following audit-led control of routine antimicrobial treatments. Performance management had been abetted by the continuous production of data on housing and flock conditions including litter quality, temperature, feed and water in-take, bird weights, carbon dioxide (CO_2) and other air quality measurements:

> "They're [veterinary data firm] putting in lots of sensors in the houses so we're building heat maps of the house. So, we divide the houses into quite small zones—sort of 10 square metres, that sort of size. (…) So I know what temperature, humidity and CO_2 there is in that zone, which will then build a heat map. We've been doing it for three or four years with them. (…) they collect an awful lot more data than what I have. They have a data analysis person which then looks at all this data and then at the end of the crop they come back to me with a full report on what they think is going on, on the farm" (PF2).

While farmers were sometimes overwhelmed by this 'datafication', with high installation costs and the limitations of the technology and infrastructure (including poor rural broadband services), and were concerned by the continuous vigilance and responsibility that data feeds demanded, there was an appreciation of possible efficiencies. These included 'early warning' capabilities (alarms could be sent to mobile phones to indicate increased litter moisture, house temperature or warn of low weight gain); data records used to extend the veterinarian's window of observation in order to make more informed and context-rich diagnoses; and benchmarking of practice in order to assess innovations (vaccines, experiments in air flow, feed supplements and so on) and to compare with other farms. As we saw earlier, data production was also a boon in terms of relationships with retailers, processors and assurance schemes, facilitating auditability. Data could be collated and shared across the value chain (though farmers and veterinarians, in this and other sectors, were concerned about data being harvested by processors and data analyst firms and not re-shared).

The data were used to account for any shifts in production and to inform future practice.

> "We chat [with the veterinarian] about the problems that arose during the flock compared to the last flock as well and any foreseeable problems. I think it's a template that they tend to knock out, but they tailor it to what's happened and what vaccines I had at hatch and the breed-specific vaccines and anything else and what feed rations we're going to do." (PF7).

In a sector that is characterised by speed of production and a requirement for swift action on infectious diseases, investments in farm- and flock-based data generation were shifting the veterinary and diagnostic gaze from the current flock to future crops. Data-rich systems helped to make treatment decisions more efficient (and smarter), to enhance accountability and audit trails by providing circumstantial diagnostic evidence that could circulate, and generated new evidence-based opportunities for changing inputs and management practices as a means to enhance future flock health. Nevertheless, 'knocking out analyses' also spoke to formulaic and generic approaches to what were uncertain and multifactorial operations.

If datafication tended to frame health as an approximation or departure from an average condition or standardised norm, for the veterinarians in our focus group, and for the farmers well used to uncertainty and variation, normal and abnormal would nevertheless depend on a farm's situation and context. Like expert diagnosis, this required interpretation and contextualisation. A danger expressed here, and in the discussions of diagnostic expertise, was that experience was being edged out of farming and veterinary practice (even if this set up the possibility for new kinds of knowledge practice in the form of data analysis, and machine learning). Standardisation of processes was starting to marginalise experience-led discretion and direction (and productive use of data was inhibited by poor data compatibility, and by data tending to be analysed and 'owned' off farm). In-house mobile robots and monitoring devices were starting to displace stock-person daily walk-throughs, while veterinarians were less and less likely to do farm visits (the COVID-19 pandemic and two years of industry "flock-downs" (mandatory housing and enhanced biosecurity measures during avian influenza outbreaks) had made on-line consultations a common practice). Labour shortages affected both farming and veterinary businesses, while low pay made retention of stock people difficult. Staff turnover made training less attractive to business managers. While the idiosyncrasies of animal health would remain, and farmers talked about the vital role of "seeing past the data" (PF3), there was a sense that investments would increasingly turn to normalisation and standardisation of farming rather than continuing investment in staff experience and context dependent animal health care. Setting industry standards and policing compliance were performative of a normalisation of production facilities and techniques.

Discussion and conclusions—AMR regulation and audit lock-in

An audit-led approach to governing antimicrobials in farming has achieved UK poultry sector-wide successes in terms of reduced mg/PCU, and has, on the evidence we have generated, changed farming practices. While mortality rates may have increased, there have also been changes to veterinary-farmer relations and new emphasis placed on animal health and welfare. The latter are arguably no longer luxuries of niche commodities that operate under the moral economies of a differentiated consumer market but have become conditions of production in the highly integrated UK poultry industry. Without access to routine antimicrobials to cover for the difficulties of high-volume livestock production, health and welfare have become essential to producing and selling birds in the UK. The audit has achieved these reductions through high levels of compliance in a standardised sector marked by significant vertical integration and retailer-led governance. Downward pressure on antimicrobial use has been effectively communicated though this industrial structure.

And yet, our analyses raise some important qualifiers to this Panglossian argument (cf. McKenna 2017). First, removing routine antimicrobial treatments has been made conditional, at least within standard production systems, upon the expansion and utilisation of various market and diagnostic devices (from treatment records to tests and flock monitoring systems). The high speed and low disease tolerance of poultry livestock systems make this device-rich farming critical to production and to the qualification of produce at current price points. These investments are capital-intensive and tend to favour scale as well as vertical integration. Second, these devices tend to promise clarity and transparency but, in practice, are inserted into multi-factorial decision-making routines. This produces a tension between the context-dependent, adaptive insights of skilled and experienced professionals, and the normalisation of production and health across a standardised sector concerned with managing reputational risk. This tension generates greater investment in device-led commodity control and auditability (and so, again, favours scale). Third, devices are linked to the actions and desires of market intermediaries (with their concern for numbers and reputations), resulting in pressure to normalise livestock and farm practices. Audits do more than establish relations, they also format those relations. Health in this account becomes a matter of approximation to the norm, rather than the ability of an organism to adapt to their environment (the distinction is Canguilhem's (1991 [1966])). This standardisation, which is suited to commodity control and actuarial process, side-lines conceptions and performances of health that are less easily enumerated and circulated. The result is a continuing process of audit expansion and datafication (Freidberg 2017), and the consolidation of standardised and flock-based approaches to animals and their health (Buller 2013; Blanchette 2020). Fourth, the power of diagnostics and data here is not in the delivery of accuracy or in the triumph of scientific technique (providing access to the mechanisms or causes of disease). Indeed, farmers and veterinarians both understood and articulated the limitations of diagnostic tests and data-led diagnoses. The power of devices was derived from their social texture and circumstantiality (Rosenberg 2002), their ability in this case to produce accountability, to deflect potential blame, rather than in their purported accuracy, transparency or utility. Fifth, in adopting a virtual consumer-led process to the regulation of antimicrobial uses, the predominant approach has been actuarial. That is, in the poultry sector, reductions in antimicrobial uses have been secured through installing metrological systems which are designed to improve knowledge of regularly occurring events. And yet, antimicrobial resistance may not fit comfortably within this probability-based logic. It is one of those threats that straddles probabilistic public health logics of risk and 'possibilist', emergent and potentially catastrophic threats (Lakoff 2015; Hinchliffe 2021). Finally, the result of this device-rich, actuarial system has clearly had effects in terms of headline figures of antimicrobial use, but it does not mark the end of large-scale production [or 'Big Chicken' as Mckenna (2017) calls it]. Indeed, further consolidation and intensification of the sector would be expected. Nor does it address problems of displacement of antimicrobial uses with other compensatory practices (like disinfectants) that may result in negative human and animal health outcomes, including drug resistance. The potential for means-ends decoupling (Bromley and Powell 2012) is high, as the audit process and its results focus on estimates and measures of antimicrobial uses and divert attention from the pursuit of minimising resistance. It is characteristic of what we term an audit lock-in—when the means of producing change consolidate and perpetuate forms of practice that are in themselves contributors to the situation at hand. The normative function of audit is affecting the diversity of farming practices at a time when we need to explore other versions of interspecies health (Hinchliffe 2022). Moreover, “the ecological nature of AMR” makes it an awkward fit “for the organismal- and biosecurity-oriented” world of practice that characterises this and other fields’ regulatory and legal practice (Kirchhelle and Podolsky 2022: p. 42). It has promoted a version of livestock health that is comparative, closed and norm-based, facilitated by further expansion and consolidation, at the expense of one that involves appropriate adaptation of livestock to farms and to environments. In the terms of audit culture, it may provide comforting figures and blame deflection at the same time as masking threats posed to human, animal and environmental health. In that sense, audit may be what Power (1997), following Sieber (1981), describes as a ‘fatal remedy’, where well-intentioned interventions contribute to harmful effects.

To be clear, market intermediaries have been effective in generating a precautionary as opposed to strictly evidential approach to the issue of antimicrobial use in poultry farming. Virtual consumers and audit based approaches have involved a series of mechanisms that represent “the ideal of being concerned, in some quantified fashion” (Miller 2012: p. 131). This is apparent in the energy invested in acting on the issue of AMR and the impressive reductions in antimicrobial use in GB poultry over the last 10 years. And, given the evidence base concerning the transmission of resistance from farm animals and environments to people, this may be a proportional response to the issue at hand. Nevertheless, the recent levelling off in mg/PCU amounts in meat producers, the rise in use in layers in 2019, and the re-production of logics that reward farming at scale, indicate a need to guard against complacency. The distortions of industry practices (with increases in compensatory practices (Scott Weese et al. 2022), as well as the tendency to perpetuate an illusion of control, may mask the emergence of issues and problems that can quickly become widespread. Questions regarding the ease with which potential AMR threats can become systemic or transmit across the food sector, the environmental externalities associated with poultry industry, and the extent to which current approaches to food production foster or suppress potentially catastrophic microbial events, remain. As other antimicrobial dependent UK livestock sectors follow the poultry sector’s success (with pig production spurred into action and dairy starting to discuss industry targets), and as other countries are urged to follow the UK example (FAO and VMD 2022), it is important that these facets of audit led change are considered.

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