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Exploring the animal treatment-sustainability nexus:

Integrating animal welfare and antibiotic stewardship into the sustainability agenda

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Abstract

Animals have played a crucial role in human history and development for millennia, utilised for food, fibre, livelihoods, leisure, companionship, and sociocultural functions. Humans derive various benefits from animals, but increasing global populations of kept animals (e.g., in agriculture) are generating harmful external costs related to animal welfare problems and antimicrobial resistance. For example, many farmed animal production systems configured to maximise production and resource-use efficiency prevent animals' expression of normal behaviours and positive affective states. Furthermore, antibiotic use in farmed animals is well managed to the extent that it aligns with the public health agenda; however, some antibiotics considered of lower risk to public health are used in relatively high quantities in farmed animals and are discharged into the environment with high persistence and potential toxicity to non-target organisms. The ineffective delivery of animal welfare and environmental public goods by the private sector denotes market failure.

This thesis explores the levers for incorporating the neglected considerations of animal welfare and antimicrobial stewardship into the veterinary and agriculture sustainability discourse and metrics in the UK context. Four sector-specific studies are presented, exploring this nexus in the veterinary profession, agriculture sector, commercial food supply chains, and public sector institutions. The studies afford different perspectives on these externalities, including both production and consumption as potential drivers of welfare harm and antibiotic use. They contribute to a nascent discourse within the UK's veterinary and commercial agricultural communities that is reflecting more deeply on how, as critical and influential stakeholders, these actors can support and forge a new relationship with non-human animals and other components of nature through a One Health approach. It concludes by proposing a series of recommendations, including regulations, incentives and voluntary initiatives, which align with an ecological sustainability paradigm that respects and strives for intergenerational and interspecies wellbeing.

Lay summary

Animals have played a vital role in human history and development for millennia. However, human-animal relationships are primarily shaped by what people need and want, such as increasing volumes of cheap animal-source foods. Some animal husbandry and treatment methods designed to meet such human needs are having negative impacts on animal welfare and the environment. For example, many farming systems designed to increase food production and maximise efficiency prevent animals from expressing their normal behaviours, which is an important and neglected aspect of animal welfare. As another example, antibiotic use in farmed animals is well managed to the extent that it aligns with human interests, in that UK farmed animal antibiotic use has declined substantially in recent years due to industry efforts to tackle this public health crisis. However, some antibiotics considered of lower risk to public health are being used in relatively high quantities in farmed animals, and are being discharged into the environment with high persistence and potential toxicity to environmental organisms. These examples, amongst others, indicate that animal welfare and environmental protections are not being fully and effectively delivered by the private sector.

Veterinary professionals, farmers, and policy-makers within public institutions have vital roles to play in delivering improved animal welfare and medicine stewardship. This thesis explores these roles in more detail in the UK context, and finds that more stringent regulation is required, coupled with support, incentives, and rewards for veterinary professionals and farmers. It also highlights the benefits of enacting a more balanced approach to sustainability, that values human, animal, and environmental wellbeing.

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Finally – to the billions of animals farmed for food every year. We haven’t got this right yet, but there are lots of us who won’t give up trying to make it a lot better.

Author's declaration

I declare that this thesis has been composed by myself and that the work has not be submitted for any other degree or professional qualification. I confirm that the work submitted is my own, except where work forming part of jointly-authored publications has been included. My contribution and those of the other authors to this work have been explicitly indicated below. I confirm that appropriate credit has been given within this thesis where reference has been made to the work of others.

The work presented in Chapter 3 was published in *Veterinary Record*[1] as 'Sustainability policies and practices at veterinary centres in the United Kingdom and Republic of Ireland' by Laura E. Higham, Zoe J. Halfacree, Jo Stonehewer, David H. Black, Gudrun Ravetz, Dominic Moran*, Lisa Boden*, and Catherine Oxtoby (*my PhD supervisors). All authors contributed to the final manuscript. I led and contributed to survey development; I also performed the analysis, wrote the manuscript with input from all other authors, and managed the project. This manuscript was published under an open access agreement between The University of Edinburgh and *Veterinary Record*, hence formal permission from the publishers for inclusion of this chapter was not sought, in accordance with the University's Thesis Format Guidance.

The work presented in Chapter 5 was published in the journal *Agricultural Systems*[2], as 'Benchmarking sustainability performance in UK free-range laying hen flocks' by Laura E. Higham, Ian Handel, Lisa Boden* and Dominic Moran* (*my PhD supervisors). I conceived the project with Dominic Moran and Lisa Boden, and all authors contributed to the final manuscript. I performed the analysis and data visualisations with support from Ian Handel, wrote the manuscript with input from all other authors, and managed the project. This manuscript was published under an open access agreement between The University of Edinburgh and *Agricultural Systems*, hence formal permission from the publishers for inclusion of this chapter was not sought, in accordance with the University's Thesis Format Guidance.

[1] Higham, L.E. et al. (2023) 'Sustainability policies and practices at veterinary centres in the UK and Republic of Ireland', Veterinary Record, 193(3). Available at: https://doi.org/10.1002/VETR.2998.
[2] Higham, L.E. et al. (2024) Benchmarking sustainability performance in UK free-range laying hen flocks. Agricultural Systems 221, pp 104103. Available at: https://doi.org/10.1016/j.agsy.2024.104103.

The work presented in Chapter 6 is currently in peer review for the journal *Agroecology and Sustainable Food Systems* as 'Regenerative food futures: One Health approaches to public food procurement at a UK university' by Laura E. Higham, Geoff Simm, Lisa Boden* and Dominic Moran* (*my PhD supervisors). This study was conceived by Andrew Arnott (from Edinburgh Earth Initiative, acknowledged in the manuscript) with my input, and all authors contributed to the final manuscript. I performed the data collection (interviews) and analysis, generated the visualisations, wrote the manuscript with input from all other authors, and managed the project.

Signed:

Laura Higham
15 January 2025

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List of abbreviations

AHDB – Agriculture and Horticulture Development Board

AMR – Antimicrobial resistance

AMU – Antimicrobial use

ARG – Antimicrobial resistance genes

BCE – Before the Common Era

BEVA – British Equine Veterinary Association

BSAVA – British Small Animal Veterinary Association

BVA – British Veterinary Association

BVZS – British Veterinary Zoological Society

CAFO – Concentrated animal feeding operation

CDC – Centers for Disease Control and Prevention

CE – Common Era

COP – Conference of the Parties (United Nations Framework Convention on Climate Change)

DEA – Data Envelope Analysis

DEFRA – Department for Environment, Food and Rural Affairs (UK Government)

EC – European Commission

EC50 – Half maximal effective concentration

ECDC – European Centre for Disease Prevention and Control

ECVPH – The European College of Veterinary Public Health

EFSA – European Food Safety Authority

EMA – European Medicines Agency

FAO – Food and Agriculture Organization of the United Nations

FAWC – Farm Animal Welfare Council

FSA – Food Standards Agency (UK Government)

GBP – British pound sterling

GDP – Gross Domestic Product

HERC – Human Ethical Review Committee

IIE – Investors in the Environment

IPBES – Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

ISSB - International Sustainability Standards Board

MCDM – Multi-Criteria Decision Making

MIC – Minimum Inhibitory Concentration

MRL – Maximum Residue Limit

NGO – Non-governmental organisation

NHS – National Health Service (UK)

OHHLEP – One Health High-Level Expert Panel

PCBs – Polychlorinated biphenyls

PNEC – Predicted No Effect Concentration

PSS – Practice Standards Scheme (RCVS)

RCVS – Royal College of Veterinary Surgeons

RSPCA – Royal Society for the Prevention of Cruelty to Animals

RUMA – Responsible Use of Medicines in Agriculture Alliance

RUMA CA&E – Responsible Use of Medicines in Agriculture Alliance Companion Animal & Equine

SDGs – Sustainable Development Goals (UN)

UK – United Kingdom

UN – United Nations

UNEP – United Nations Environment Programme

USA – United States of America

USD – United States dollars

VDS – Veterinary Defence Society

VMD – Veterinary Medicines Directorate

VSGs – Veterinary Sustainability Goals (Vet Sustain)

WCED – World Commission on Environment and Development

WHO – World Health Organization

WOAH – World Organisation for Animal Health

WVA – World Veterinary Association

1. Introduction

Animals have played a crucial role in human history and development for millennia. From the time of early hunter-gathers and the settled agrarian communities that formed the foundations of modern complex societies (Frantz *et al.*, 2020), humans have utilised animals for food, fibre, livelihoods, leisure, companionship, and social cohesion (Livestock in Development, 1999). However, human-animal relations have evolved significantly in space and time, based on the animal species, purpose, and socio-cultural significance, as well as developments in animal science and philosophy.

Today, scientific evidence and public perception of animal sentience is underpinning a growing concern for animal welfare in the United Kingdom (UK) and other regions, against a backdrop of increasing farmed animal populations and agricultural intensification in pursuit of food production and resource-use efficiency. The silent pandemic of antimicrobial resistance with One Health impacts[3] is in-part attributed to animal antibiotic use, which is nevertheless both an enabler and a consequence of modern farming systems. With anthropocentric worldviews dominating policy responses to the multifaceted global sustainability crisis, activities that enhance human service to animals have been deprioritised. Hence, animal welfare problems and antimicrobial resistance represent harmful externalities arising from the food system, which are inadequately managed by public policy, partly due to the specific nature of market failures that give rise to both.

This thesis explores the animal treatment-sustainability nexus, and the levers for incorporating the neglected considerations of animal welfare and antimicrobial stewardship into the sustainability discourse and metrics. Although this challenge has not been well-addressed in any region, these chapters primarily focus on the UK context. It is suggested that veterinary professionals, agricultural stakeholders

[3] One Health is an integrated, unifying approach that aims to sustainably balance and optimise the health of people, animals, and ecosystems. It recognises the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are closely linked and inter-dependent. (OHHLEP, 2020)

(producers, processors, retailers, and other food business actors), and policy makers hold crucial roles in this field, and that better metrics could help them target their roles in the management of the animal treatment dimensions of the sustainability agenda. Specifically, this thesis responds to five research questions:

(1.) Where or how are animal welfare and antimicrobial stewardship located in the sustainability agenda?

(2.) What are the roles of veterinary, agricultural, and public sector stakeholders in supporting animal welfare and antimicrobial stewardship as sustainability objectives?

(3.) What are the barriers to advancing animal welfare and antimicrobial stewardship as facets of sustainability?

(4.) What actions could be taken to leverage the roles of veterinary and agricultural stakeholders in improving animal welfare and antimicrobial stewardship as dimensions of sustainability?

To meet these aims, four sector-specific studies have been undertaken, scrutinising aspects of sustainable animal treatment by: (a) veterinary professionals in clinical practices; (b) the agriculture sector in their use of veterinary medicines; (c) stakeholders in commercial food animal supply chains; and finally (d) public sector institutions, through food procurement practices. This diverse collection of studies affords different perspectives on the nexus problem, including both production and consumption as potential drivers of sustainable animal treatment. The thesis contributes to what was otherwise a nascent discourse advancing the argument that veterinary and agricultural stakeholders can support and forge a new relationship with non-human animals and other components of nature, that respects their instrumental and intrinsic value.

This thesis is structured as follows. Chapter 2 presents a literature review exploring elements of animal welfare and antimicrobial stewardship in the animal agricultural sustainability context. Chapter 3 describes a survey administered to identify sustainability policies and practices at clinical veterinary centres in the UK and the Republic of Ireland. Following the veterinary theme, Chapter 4 assesses the impact of veterinary antibiotic use in terrestrial farmed animal species on the environment

and non-target organisms. To explore the multiple and competing dimensions of sustainability, including welfare and antibiotic use, Chapter 5 presents an empirical study using the linear programming technique Data Envelope Analysis to benchmark the sustainability performance of laying hen flocks within a UK commercial egg supply chain. Chapter 6 moves from production to the consumption side by using key informant interviews and Thematic Analysis to understand the desired sustainability objectives (including animal welfare) and perspectives on 'regenerative' approaches to public food procurement amongst members of a university community. Chapter 7 offers conclusions. Each of the four research projects within this thesis are either published (Chapters 3 and 5), in peer review (Chapter 6), or prepared for journal submission (Chapter 4).

Ethical approval was granted for the studies in Chapter 3 and Chapter 6. The survey on veterinary centre policies and practices featured in Chapter 3 received ethical approval from the Royal College of Veterinary Surgeons (RCVS) Ethics Review Panel (Reference 2022-090-Oxtoby). The study based on key informant interviews amongst a university community documented in Chapter 6 received ethical approval from the Human Ethical Review Committee (HERC) at the Royal (Dick) School of Veterinary Studies in May 2023, under application number HERC_2023_070. The remaining studies and chapters did not involve human or animal participants and thus did not warrant ethical approval. However, the benchmarking study featured in Chapter 5 involved the analysis of anonymous data from egg producers, and was subject to a tripartite data sharing agreement between the egg packing company, FAI Farms, and the University of Edinburgh.

2. Sustainability and its neglected domains

This chapter introduces the concept of sustainability and its current and emerging dimensions. The chapter seeks to clarify where animal welfare and antimicrobial stewardship are situated in relation to sustainability definitions. Addressing research question 1, the chapter then characterises these two issues as expressions of human treatment of animals and neglected sustainability domains.

2.1 Sustainability

With the current environmental trajectory including climate change, habitat loss, species extinctions, and alterations in the chemical composition of the atmosphere, oceans and soil, the planetary boundaries that define the safe operating space for humanity are being transgressed (Rockström *et al.*, 2009). Related health and social disparities are prevalent and increasing, including the triple burden of malnutrition, in-country inequality, non-communicable illnesses, zoonotic disease, and antimicrobial resistant infections (Cascio *et al.*, 2011; Collignon *et al.*, 2018; Chancel *et al.*, 2022; Food and Agriculture Organization of the United Nations (FAO), 2022). Normalised, harmful uses of animals are diminishing the welfare of domestic animals and wildlife to satisfy human demands, including in the pursuit of low-cost animal-source foods (McInerney, 2004; Butterworth, 2018).

The growing imperative to address these multiple crises has generated several definitions and frameworks for sustainability. The most widely used definition was proposed in the context of ‘sustainable development’ in the United Nations (UN) Brundtland Report (World Commission on Environment and Development (WCED), 1987): “*development which meets the needs of current generations without compromising the ability of future generations to meet their own needs*”. Although this framing paved the way to the concept of intergenerational justice (Naudé, 2017), it prompted the widespread adoption of an anthropocentric worldview of sustainability, which prioritises human development over the needs of other species

(Purser *et al.*, 1995; Borland and Lindgreen, 2013), and fails to acknowledge the biophysical and ethical-spiritual limits within which society must operate (Porritt, 2012). Lomborg (2001) defends anthropocentric attitudes by suggesting that non-human species cannot be fairly represented by humans, and therefore this shouldn't be attempted - which supports a socially-constructed human-nature dualism and hierarchy (Borland and Lindgreen, 2013; Allen *et al.*, 2019).

Several frameworks depict selected sustainability concerns through an anthropocentric lens: the UN Sustainable Development Goals (SDGs) address challenges across the social and environmental domains to create a "*shared blueprint for peace and prosperity for people and the planet, now and into the future*". The concept of the 'Planetary Boundaries' examines the environmental pressures and thresholds that define the "*safe operating space for humanity*" (Richardson *et al.*, 2023). Global standards for sustainability disclosures devised after the Conference of the Parties (COP) 26 by the International Sustainability Standards Board (ISSB) provides a framework for companies to report climate-related risks affecting their financial prospects (International Financial Reporting Standards Foundation (IFRS), 2023), and will form the basis of future UK legislation and regulation (UK Government, 2023c).

Sustainability issues can be characterised in terms of instrumental metrics of use and substitutability of capital resources. Economists delineate resources into four main capital types (or stocks), from which flows of utility (human wellbeing) are derived. These forms of capital include manufactured, human, social, and natural capital, with a fifth – financial capital – representing the value of the other types (Buriti, 2018). Viewpoints around the extent to which capital stocks can be used and substituted for one another - while maintaining intra- and inter-generational welfare flows - underpin the concepts of *'weak'* and '*strong'* sustainability (Pearce and Atkinson, 1993; Buriti, 2018). Proponents of weak sustainability, aligned with anthropocentric viewpoints, mostly assert that natural capital stocks can be used and replaced/substituted by other forms of natural capital and/or forms of manufactured capital (e.g., technological solutions) in some circumstances. Welfare flows are basically uninterrupted by substitution possibilities, these in turn unlocked by human

ingenuity[4]. Strong or 'ecological' sustainability, in contrast, advocates the non-substitutability and regeneration of many natural resource stocks; it places binding thresholds or tipping points on capital stocks including ecosystems, and promotes interspecies and intergenerational justice and sometimes intrinsic value arguments (Purser *et al.*, 1995; Padilla, 2002; Borland and Lindgreen, 2013). Table 1 condenses and simplifies these two sustainability epistemologies and their associated values, comparing the modus operandi for sustainability management (anthropocentric sustainability) and an ecological paradigm.

Table 1: A comparison of anthropocentric and ecological sustainability paradigms (Adapted from Borland and Lindgreen, 2013, and Buriti, 2018).

Paradigm	**Anthropocentric sustainability** *Weak sustainability* *Substitutability*	**Ecological sustainability** *Strong sustainability* *Non-substitutability*
Value set	Human-centred Instrumental value of ecosystems Rational Egocentric Intra-generational Economic growth Substitutability of all forms of capital	Ecosystem-centred Intrinsic value of ecosystems Ecological rationality Empathetic Inter-generational Wellbeing across species Natural capital requires preservation
Scientific approach	Technological solutions Reductionist Empirical	Holistic solutions Embraces complexity Systems-based
Strategy	Sustainable development Transitional Competitive Incremental Linear Cradle-to-grave Open-loop Eco-efficient	Regeneration Transformational Collaborative Systems change Circular Cradle-to-cradle Closed-loop Eco-effective

The hegemonic anthropocentric worldview emphasises human development including economic growth and prosperity, in effect defaulting to a weak sustainability trajectory and potentially deprioritising and compromising an array of interlocking sustainability issues of importance to society. In economics terms, these neglected issues manifest as external costs, or externalities. When capitals stocks – including commoditised animals – are 'converted' into public and private goods and

[4] Techno-optimism

services under conventional and extractive supply chain structures, the associated conversion processes typically fail to internalise (i.e., reward or penalise) the generation of good/bad impacts. Amongst these externalities are those resulting from our treatment of animals (Barrett *et al.*, 2021; Sinclair *et al.*, 2022).

Animal welfare problems and antibiotic resistance are externalities arising from anthropocentric human-animal relations configured to generate goods and services. In the environmental-economic sense, they can be considered as by-products of production processes (food production and husbandry) that are an adjunct to the natural environment. As such, they can also be accommodated within the aforementioned sustainability rhetoric as well as other disciplinary frameworks, such as the Ecosystem Approach (COP5, 1999) and latterly the 'One Health'[5] rhetoric, linking animal health and welfare to human and environmental health endpoints (One Health High-Level Expert Panel (OHHLEP), 2020). These neglected sustainability domains are discussed in detail in the following sections.

2.2 Animal welfare

Animal welfare has been defined as *"the physical and mental state of an animal in relation to the conditions in which it lives and dies"*, in the World Organisation for Animal Health (WOAH)'s Terrestrial Animal Code (WOAH, 2022b). Similarly, the UK Government's Brambell Report described it as *"a wide term that embraces both the physical and mental well-being of the animal"* (Brambell, 1965). The following section reflects on the historical development of these animal welfare concepts, to describe their importance to society and interface with sustainability paradigms.

2.2.1 A brief history of animal welfare

Over the course of millennia, the moral consideration of other humans and non-human species within society has evolved substantially (Broom, 2011), informed by

[5] One Health is an integrated, unifying approach that aims to sustainably balance and optimise the health of people, animals, and ecosystems. It recognises that the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are closely linked and inter-dependent. (OHHLEP, 2020)

a range of cultural and religious ideologies. In the Indus Valley Civilization (from 3300 BCE), it was supposed that animals were reincarnations of human ancestors and must therefore be treated with respect. These philosophies are reflected in the religious teachings of Jainism, Hinduism, and Buddhism today, which promote non-injury to living beings (*ahisma*). From the 6th Century BCE, The Old Testament describes human dominion over the animal kingdom and natural world, but describes animals as beings with interests that deserve respect (Gatward, 2001). In Islam, the Qur'an (circa CE 650) teaches that Allah has given people power over animals, but to treat animals in a bad manner is to disobey Allah's will (Szucs *et al.*, 2012). Such religious teachings have substantially evolved. They are briefly mentioned here to illustrate the ancient origins of animal welfare concepts that pre-date the contemporary European animal welfare movement that often dominates the literature.

Ancient ideologies were followed by a philosophical doctrine that prevailed in Europe, premised upon species differences. European philosophers Aristotle (384-322 BCE) and others introduced and promoted the idea that it was the ability to reason (rationality) that made human beings distinct from all other animals, affording them only *instrumental value* and no moral standing. Much later, Descartes (1596-1650) suggested that animals express emotions, yet he presented the idea of animals as 'automata', or machines. As a keen vivisectionist, he dissected live conscious animals, suggesting he believed animals' emotions to be somewhat unconscious (Duncan, 2006).

In the early Enlightenment period (1600s), unnecessary cruelty towards animals was condemned on the grounds of morality and animal 'sentience' – a concept defined by Broom (2011): *"A sentient being is one that has some ability: to evaluate the actions of others in relation to itself and third parties, to remember some of its own actions and their consequences, to assess risk, to have some feelings and to have some degree of awareness".* Writings on the subject in the 1600s were, however, predated considerably by many of the great, artistic works of the Renaissance period, indicating that animal sentience was accepted as part of secular knowledge (Preece, 2002). The practice of live animal dissection was challenged in 1700s by philosophers including Voltaire based on animal sentience, who noted that if you

dissect a dog, *"you discover in him all the same organs of feeling as in yourself. Answer me, mechanist, has Nature arranged all the springs of feeling in this animal to the end that he might not feel?"* Later in the Enlightenment period in Europe, social reformer Jeremy Bentham (1748-1832) disputed previous claims regarding rationality as the bedrock of moral standing, and highlighted the importance of sentience, famously writing: *"The question is not, Can they reason? nor, Can they talk? But, Can they suffer?"* (Bentham, 1781).

This evolving human understanding of animal feelings reflects a growing acknowledgement of human-animal similarities. Indeed, a clear relationship exists between similarity and preference, suggesting that humans are predisposed to liking other species on the basis of shared bio-behavioural traits (Batt and Davies, 2009). In fact, an emphasis on perceived 'difference' has, over the course of human history, underpinned inter- *and* intra-species inequity and exploitation, with poignant and pervasive examples in slavery and gender inequality. Equity narratives also cut across species lines in campaigns for the rights of multiple marginalised groups. For example, the published animal welfare discourse has traditionally and predominantly been shaped by the voices of male European philosophers; however, the mid- to late-19th century saw a movement of women animal rights influencers including Frances Power Cobbe (1822–1904), Caroline White (1833–1916), Anna Kingsford (1846-1888), Nina Douglas-Hamilton (1878-1951) and "Lizzy" Lind of Hageby (1878-1963). Many of these women fought for both gender equality *and* animal protections (Gaarder, 2011), reflecting an interspecies allyship that challenged the notion of difference as grounds for inequitable treatment[6]. Based on the visibility and leadership positions attained by these women through lobbying (Ferguson, 1998), it is suggested that animal rights activism was a precursor to and facilitator of the Suffragette movement in Britain (Divers, 2018). Recent research indicates that concern for animal welfare is consistently related to greater concern for human welfare (Deemer and Lobao, 2011).

At a similar time, the concept of animal sentience was gaining traction in scientific circles. Unqualified but practicing English veterinarian William Youatt (1776-1847)

[6] Note that by the late 1800s in England, animals were granted more rights than women (Bourke, 2011).

supported the concept, writing: *“We are operating on animals that have, probably, as keen feelings of pleasure and of pain as ourselves”* (Youatt, 1839). Youatt’s books were followed by the work of Darwin (1809-1882), namely The Expression of the Emotions in Man and Animals (Darwin, 1890), in which he described similarities in animal and human emotions, suggesting a shared evolution.

Parallel to developments in animal welfare philosophy and science, advances were also made in legislation: One of the earliest animal protection laws in Europe was enacted in Ireland in 1635, which prohibited pulling wool off sheep and attaching ploughs to horses' tails, describing both practices as a form of *"cruelty…to beasts"* (Grierson, 1794). Laws against animal cruelty followed in 1641 in Massachusetts Bay Colony, USA, and later in the 1690s in Japan, where Tokugawa Tsunayoshi, the ‘Dog Shogun of Japan’, passed laws protecting dogs from abuse (Bodart-Bailey, 2006). In England in the late 17th century, a specific piece of legislation was introduced: Martin’s Act (1822) protected cattle and horses, and was later amended in 1835 to include all domestic animals (Great Britain Parliament, 1835).

Following the Second World War, farm animal production rapidly intensified in response to the demand for food security and cheap food in the UK. Production systems formerly dependent on labour for routine tasks evolved into a new generation of processes involving automation and the confinement of animals in specialised indoor environments. These farming methods were largely deployed in the absence of public awareness and scrutiny, until they were exposed in a seminal publication by Ruth Harrison (1920-2000), *Animal Machines* (Harrison, 1964), which emphasised the scale of animal suffering resulting from intensive farming. The book followed Rachel Carson’s Silent Spring (1962) on the environmental harm caused by pesticide use, amounting to a movement in the 1960s scrutinising intensive agriculture.

The public reaction to Harrison’s book stimulated the UK’s Ministry of Agriculture to form a Committee of Enquiry chaired by Professor F.W.R. Brambell. The subsequent publication of ‘The Brambell Report’ (Brambell, 1965) led to an Act of Parliament governing farm animal welfare and laid the foundations for the Five Freedoms, which

were later formalised in a press statement by the UK's Farm Animal Welfare Council (FAWC) in 1979.

The Five Freedoms of animal welfare - based on Brambell (1965) and updated by FAWC (1979, 1993)

1. *Freedom from hunger and thirst* by ready access to fresh water and diet to maintain health and vigor.
2. *Freedom from discomfort* by providing an appropriate environment including shelter and a comfortable resting area.
3. *Freedom from pain, injury, or disease* by prevention or rapid diagnosis and treatment.
4. *Freedom to express normal behaviour* by providing sufficient space, proper facilities, and company of the animal's own kind.
5. *Freedom from fear and distress* by ensuring conditions and treatment which avoid mental suffering.

2.2.2 The Five Freedoms and beyond

The Five Freedoms continue to underpin modern definitions of animal welfare, as well as the legislation and codes of practice established in the decades that followed their inception. With growing acknowledgement of animal feelings, consciousness, and cognition over the course of millennia, the Five Freedoms enshrines the concept of sentience as a core justification for supporting high standards of animal treatment. However, despite their rise to prominence in response to the intensification of agriculture, the Five Freedoms have not been fully translated into policy governing all farming systems in Europe, particularly regarding the provision of normal behavioural opportunities. For example, farrowing crates for sows are allowed and widely used across the UK and Europe, prohibiting mobility and nest building during the periparturient and lactation period.

Furthermore, with a primary focus in the Five Freedoms on reducing negative, unpleasant experiences and providing for basic *needs*, animal welfare scientists have since recognised the importance of cumulating, positive, and pleasant experiences and providing what animals *want* (Dawkins, 2021; Reimert *et al.*, 2023). Indeed, FAWC characterises high standards of welfare as providing "*a good life*" for animals (FAWC, 2009), and Dawkins (2021) describes animal welfare as "*health, and animals having what they want*". Acknowledging the importance of affective states, Mellor (2017) proposed the 'Five Domains' model, which considers the negative *and* positive experiences arising from physical and functional factors, influencing the overall mental state and welfare of the individual animal. Moreover, Fraser (2003) identified three value-dependent views of animal welfare, including those focused on the biological functioning of the animal (objective); the emotions experienced by the animals, or affective state (subjective); and the similarity between the animal's behaviour or environment, and those of the natural state of the species (natural living).

Reflecting on good physical health and mental wellbeing (including positive affective states) as two building blocks of animal welfare, several frameworks have emerged to evaluate environments for kept animals in terms of their provision for animal 'needs' *and* 'wants'. These tools move beyond resource-based *input* measures (e.g., space provision; provision of enrichment), to include animal-based health and welfare *outcome* measures (e.g., mortality; severity and prevalence of lameness). For example, the Welfare Quality® protocols were constructed as species-specific multidimensional tools for capturing inputs and outcomes across the four welfare principles of 'good feeding, good housing, good health, and appropriate behaviour' (Forkman and Keeling, 2009). The Welfare Quality® Project was followed by The European Animal Welfare Indicators Project (AWIN) (Scotland's Rural College (SRUC), 2015) to develop a more concise suite of measures, addressing practical limitations of the former tool's lengthy assessment process.

These programmes paved the way to the adoption of welfare outcome measure assessment and reporting in farmed animals as part of private assurance schemes (Royal Society for the Prevention of Cruelty to Animals (RSPCA), 2017), industry tools (Agriculture and Horticulture Development Board (AHDB), 2024), non-

governmental organisation benchmarks (Amos *et al.*, 2021), and emerging UK farming policy (Department for Environment, Food and Rural Affairs (DEFRA), 2020). Reliable and repeatable measures of good animal health are relatively simple to collect, but animal emotions have been more challenging to measure and validate. Frameworks have generally included physiological observations as proxy indicators of an animal or animal group's welfare experience (e.g., feather scores for laying hens); however, qualitative behavioural assessment (QBA) using human judgement represents a new frontier for reliably and repeatably discerning an animal's mental state (Wemelsfelder, 2008).

2.2.3 The economics of farmed animal welfare

The previous section describes a rise in animal welfare concern in philosophy, science, and legislation, with a growing number of tools and frameworks available for the practical assessment of animal welfare states within husbandry systems and commercial settings. These developments reflect a growing perception amongst citizens that farm animal welfare should be improved (Alonso *et al.*, 2020); e.g., 84% of Europeans claim that the welfare of farmed animals should be better protected (European Commission (EC), 2023). Animal welfare has often been described as a 'public good'; i.e., it is non-excludable and non-rival in consumption[7], and it is within the public interest for governments to ensure its protection (McInerney, 2004; Hubbard *et al.*, 2020). Hence, animal welfare is enshrined in law corresponding to society's approximate norm/demand for good welfare in production, and private suppliers are sanctioned if these laws are not respected.

Such legislation in the UK provides protections for animals to a certain standard, but a science-policy gap remains in the wide-scale adoption of animal production systems that assure both good animal health *and* mental wellbeing (including positive affective states). For example, UK animal welfare legislation permits housing systems that deny normal behaviours (e.g., close confinement of laying hens and farrowing sows), genetics associated with harmful disease predispositions (e.g., fast-

[7] Goods and services can be defined by the characteristics of excludability and rivalry in consumption. A good is *excludable* when its consumption requires payment: if you do not pay then you are excluded from consuming it. A good is *rival in consumption* when the same unit of a good cannot be consumed by more than one individual at the same time. Public goods are both non-excludable and non-rival in consumption (Hubbard *et al.*, 2020).

growing broiler chickens and dystocia-predisposed beef cattle), and husbandry practices involving feed restriction and therefore hunger (e.g., fast growing broiler breeders). Therefore, the basic standards enshrined in UK legislation protect animal welfare to the extent that it coincides with human interests (Nurse, 2016). Beyond this threshold, animal welfare - including consideration of affective states – is currently delivered by the free market and treated as a private good (McInerney, 2004). The threshold for defining the legal statute in relation to private operations and their associated supply of public goods is ultimately a compromise within the specific country and context - reflecting where the publics' preferences are thought to lie, and who should pay (and how) for providing the public good element.

Higher levels of farmed animal welfare including normal behavioural opportunities and the potential for positive affective states, are therefore delivered through private market transactions, and are codified in retailer standards and food assurance scheme labels. Research from Belgium indicates that consumers view animal welfare *more* in terms of affective states and natural living, than biological functioning (Vanhonacker *et al.*, 2008), suggesting they would support higher-tier animal welfare schemes assuring behavioural opportunities. However, willingness-to-pay studies consistently show that citizens' stated preferences towards farm animal welfare do not always translate into consumer purchasing decisions (Toma *et al.*, 2011; Clark *et al.*, 2017). This paradox has been coined the 'consumer–citizen duality' by Vanhonacker et al (2007), and can arise from conflicting priorities, insufficient information, cognitive dissonance amongst consumers (Hubbard *et al.*, 2020), and perhaps a view that public goods should be provided by state subsidy rather than through private good transactions. As a result, higher welfare-labelled animal products account for a small market share: only 12% of pig meat on retail sale in the UK carries the 'outdoor' claim[8], with products in this category almost twice as expensive per kilogram as conventional pork (AHDB, 2021).

This example portrays voluntary schemes within free markets as inadequate levers for enacting higher animal welfare standards that include positive affective states for many farmed animals in the UK food system. The free market's inability to produce

[8] Includes outdoor bred, outdoor reared, and free-range.

an optimal public good outcome for society, with poor animal welfare representing a negative externality of food production, is indicative of market failure.

2.2.4 Animal welfare and sustainability

Despite its growing prominence as a societal concern, animal welfare has traditionally been absent from the global sustainability discourse, such as the 17 UN SDGs, and FAO's anthropocentric definition of sustainable agriculture: *"To…meet the needs of present and future generations, while ensuring profitability, environmental health, and social and economic equity."* (FAO, 2024) However, in alignment with the One Health framework (OHHLEP, 2020), animal welfare is increasingly appearing in contemporary sustainability narratives, such as the UN's updated SDG Agenda for 2030 (UN, 2015b), which declares: *"We envisage a world in which every country enjoys sustained, inclusive and sustainable economic growth and decent work for all. One in which humanity lives in harmony with nature and in which wildlife and other living species are protected".* (UN, 2015b)

In fact, improving animal welfare may be synergistic with the attainment of other sustainability goals – a study by Keeling *et al.* (2019) involving a scoring exercise by expert participants found no conflict between achieving any of the 17 UN SDGs and improving animal welfare. In most cases, it was considered more likely that achieving an SDG would improve animal welfare, than improving animal welfare would help to attain an SDG. This suggests that animal welfare may be a passive beneficiary of sustainable development, but that animal welfare improvements may, once again, only improve to the extent that they align with human interests, with certain facets of animal welfare selectively improved in the pursuit of anthropocentric goals.

As one of the facets of animal welfare, physical health (Stamp Dawkins, 1980; Dawkins, 1990; Broom, 2011) contributes to mental wellbeing *and* underpins the instrumental or 'use value'[9] of animals to people. In many anthropocentric animal use settings such as food animal supply chains, sport, and entertainment, goods and services are primarily derived from and contingent upon the physiological function or

[9] 'Use value', or 'utility', denotes the tangible features of a commodity that can satisfy some human requirement, want, or need.

biomass of animals, based on physical health and condition. Broom (2011) notes that animal welfare has traditionally been associated with the treatment or prevention of disease, with animal behaviour and brain function considered to be of peripheral importance to veterinary work. Furthermore, the commercial success of confinement production systems indicates that poor mental wellbeing does not always jeopardise the physical health, fitness, and anthropocentric use value of farmed animals. As a result, health has dominated and overshadowed mental wellbeing in the animal welfare discourse.

Figure 1 illustrates how functions of physical health (i.e., the health, nutrition, and environment domains) constitute the basic building blocks of animal welfare, but additional provisions for mental wellbeing (i.e., behaviour and mental state) are necessary for an animal to reach its welfare potential. Although mental wellbeing is partly dependent upon physical health, physical health and production are not always dependent on mental wellbeing. Exceptions to this arise where negative affective states such as hunger, frustration, and boredom manifest as aversive behaviours that impair physical health or condition, such as maternal savaging and tail biting in pigs, or feather pecking and cannibalism in laying hens.

Figure 1 helps to illustrate the notion that many standards and regulations support animal welfare in terms of the physical health domains, whilst deprioritising mental wellbeing. For example, viewed through the Five Freedoms ('absence of negative states') framework, the physical health of animals may be considered good within a close confinement environment or in a broiler breeding programme involving feed restriction; yet behavioural opportunities, mental states, and the pursuit of positive outcomes across all domains are lacking. This has arisen in part due to the co-benefits to human interests of optimising physical animal health with associated use value, alongside inadequate protections to nurture mental wellbeing as an additional welfare dimension with public good and non-use value[10] attributes, but with limited market traction. However, as discussed later, citizens are increasingly expressing the need for animal welfare to carry intrinsic weight in public decision making

[10] Non-use value is the value that people assign to goods or services, even if they never have and never will use it. Non-use value includes 'existence value' (derived from knowing something exists), 'paternalistic altruism' (derived from others' use of a good), and 'bequest value' (from the desire of individuals to preserve a good for the use of future generations) (Lagerkvist *et al.*, 2011).

(Johansson-Stenman, 2018), supporting an ecological sustainability paradigm aligned with interspecies wellbeing.

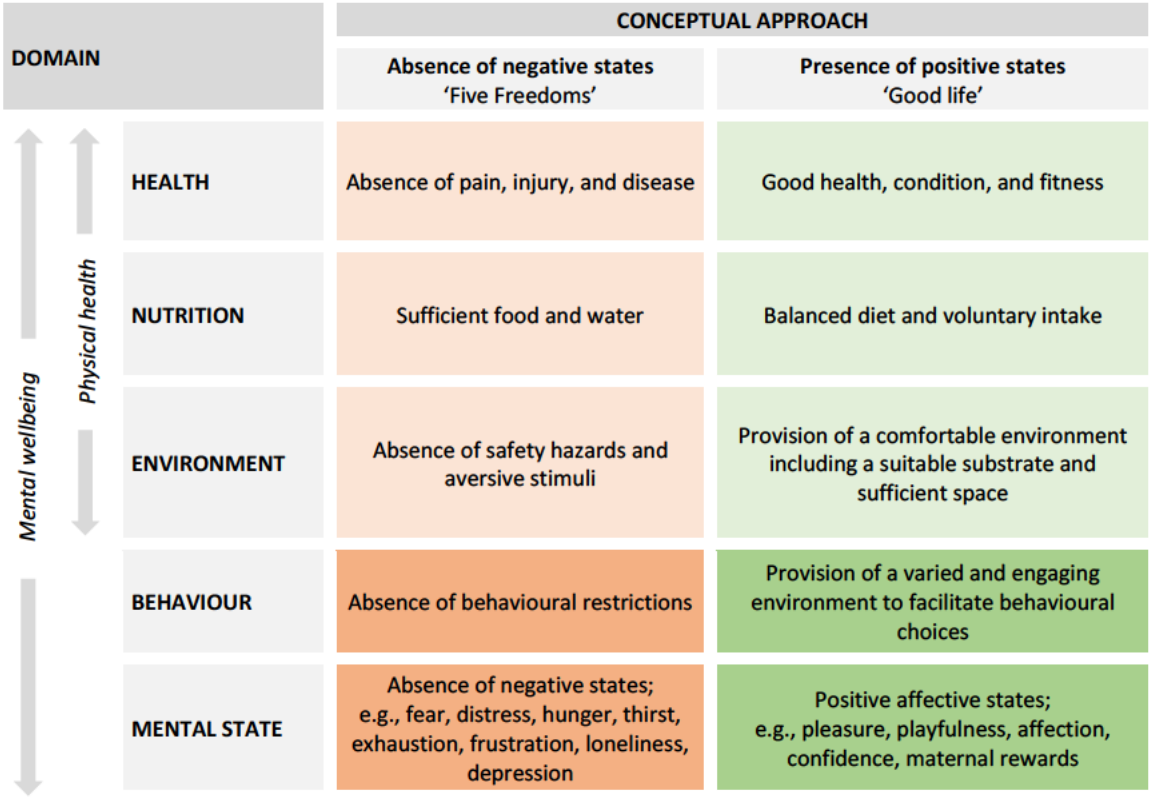

Figure 1: The five domains of animal welfare (according to Mellor and Reid 1994), and their interpretation through two alternative conceptual approaches of The Five Freedoms and absence of negative states (FAWC 1979), and The Good Life concept and presence of positive states (FAWC 2009).

2.3 Antimicrobial use (AMU) and resistance (AMR)

Another concern relating to animal treatment is antimicrobial resistance (AMR) - the ability of microbes[11] to grow or survive in the presence of an antimicrobial[12] agent. An escalating global health threat, the phenomenon is eroding the therapeutic efficacy of antimicrobial compounds, and therefore the toolbox of antibiotic resources

[11] The term 'microbe' applies to all microscopic organisms including bacteria, viruses, fungi, and protozoa.
[12] Antimicrobials are naturally occurring, semi-synthetic or synthetic substances that kill or inhibit the growth of microbes, and antibiotics are a specific as a sub-set of antimicrobials, which act to kill or inhibit the growth of bacteria. With a focus on the problem of antibiotic resistance, and in line with European Food Standards Authority (EFSA) (Andreoletti *et al.*, 2008), the terms 'antimicrobial' and 'antibiotic' will be used interchangeably in this thesis.

for treating infections in humans, animals, and plants. Existing data preclude an accurate impact assessment of the current global health burden of AMR and its future trajectory (Woolhouse *et al.*, 2016); however, the UK Government report by Lord O'Neill (2016) attributed an estimated 700,000 human deaths per year rising to 10 million by 2050 to AMR, with a predicted cumulative cost to global economic output of 100 trillion USD.

The most significant risk factors for AMR in human patients are underlying disease, antibiotic use, and invasive procedures in health-care settings (Chatterjee *et al.*, 2018). However, there is a growing consensus that antimicrobial use (AMU) in food animal agriculture is a key driver of resistance pressure (European Centre for Disease Prevention and Control (ECDC) *et al.* 2017, Tang *et al.* 2017) and a precursor to diffuse pollution with antibiotics and resistance determinants, with human, animal, and environmental consequences (Bengtsson and Greko, 2014; Moran, 2019). Indeed, AMR is considered a quintessential 'One Health' challenge (Moran, 2019).

In this section, a background on antibiotic discovery and application is presented, before AMU is depicted in the sustainability context as both an enabler and a consequence of anthropocentric human-animal relations, with AMR emerging as a harmful externality.

2.3.1 Antibiotic use in agriculture

Naturally-occurring antibiotics have been extracted and utilised by humans for centuries, with early records documenting the use of filamentous fungi growing on bread and copper salts in the treatment of wounds and burns in ancient Egypt (Pećanac *et al.*, 2013). During the development of modern medicine in the 19th century, scientists began to observe the inhibitory effects of various moulds and bacteria on infections, and by the early 1900s, derivatives of natural antibiotics were being commercialised. In Britain, sulfochrysoidine was the first antibiotic marketed for animal use from 1938, with other agents including gramicidin and penicillin introduced shortly after (Kirchhelle, 2018).

At a similar time, driven by post-war policies to improve food security and maximise production, farmed animal populations and farm sizes began to grow in the UK and other regions, accompanied by a transition to intensive farming systems (Robinson and Sutherland, 2002). Since 1945, Great Britain recorded a 65% decline in the number of farms, a 77% reduction in farm labour, and a four-fold increase in yield associated with mechanisation and increased application of chemicals (Robinson and Sutherland, 2002). Similarly in the USA, animal numbers on small to medium-sized farms decreased significantly between 1982 and 1997, but animals produced in concentrated animal feeding operations (CAFOs)[13] increased by 88% (US Environmental Protection Agency (EPA), 2003; Kellogg *et al.*, 2011). This growth trend is also evident at global level, reflecting the rising demand for animal-source foods from a growing and urbanising human population (Speedy, 2003; Van Boeckel *et al.*, 2015) (see Table 2).

Table 2: Global production of animal-source products between 1961 and 2018 (data from FAO, 2020).

Product	Global production in tonnes, by year		Factor change (1961-2018)
	1961	2018	
Poultry meat	8,949,668	127,298,325	↑ 14.2
Eggs	15,109,946	82,934,177	↑ 5.5
Pig meat	24,748,623	120,881,269	↑ 4.9
Sheep and Goat Meat	6,032,191	15,765,334	↑ 2.6
Beef and Buffalo Meat	28,755,714	71,601,312	↑ 2.5
Milk	344,184,775	843,035,456	↑ 2.4

These changes in 20th century agriculture exemplify a trajectory of intensification, concentration, and specialisation, in pursuit of greater resource use efficiency (Tamásy, 2013). Efficiency gains have been achieved through a variety of means, including increased herd and flock sizes, higher stocking densities, greater use of mechanisation, the introduction of confinement production systems, selective breeding for productivity attributes, reduction in genetic diversity, and increased use of input resources - including antibiotics.

[13] Concentrated animal feeding operations (CAFOs) are intensive animal feeding operations in which over 1,000 animal units are confined for over 45 days a year (US EPA, 2024).

In the post-war era, researchers trialled the use of mass medication with antibiotics in herds and flocks within concentrated animal operations, to control disease and minimise the labour costs associated with individual animal care (Kirchhelle, 2018). In 1948, the first in-feed antibiotic sulfaquinoxaline was licensed for the routine prevention of coccidiosis (Kirchhelle, 2018), and later in the 1950s, scientists in the USA discovered that the addition of antibiotics and vitamin B12 to animal feed accelerated growth (Ogle, 2013). Despite early warnings from the scientific community of the risk of AMR (‘Infectious drug resistance’, 1966), AMU became globally widespread on farms, whaling and fishing fleets, processing plants, and aquaculture operations, deployed to treat and prevent disease, increase feed conversion, promote growth, and preserve food (Kirchhelle, 2018).

The rapid integration of AMU into the global food system was linked to the intensification of agriculture - a co-evolution that occurred in pursuit of post-war food security, development, and prosperity, and alongside an expanding toolbox of antibiotic resources (Kirchhelle, 2018). In this context, routine AMU was both an *enabler* and a *consequence* of modern animal production systems: Cameron and McAllister (2019) consider AMU to be a critical and indispensable component of contemporary farmed animal production, enabling some systems to maintain current production levels by preventing and controlling animal disease (Buller *et al.*, 2015). Woods (2019) clarifies, however, that antibiotic use represents only one of several tools that were deployed to counter the diseases associated with intensive animal production, with other innovations addressing housing, husbandry, and nutrition. Antibiotic use was therefore *one of several* concurrent enablers of agricultural intensification. Additionally, an increased need for antibiotics may be a consequence of the inherent disease risks associated with confinement (Barnett *et al.*, 2001), high stocking densities (Hu and Cheng, 2016; Lekagul *et al.*, 2019), yield-oriented breeds (AVINED, 2020, see Table 3), and other modern husbandry practices (Murphy *et al.*, 2017).

Table 3: Slower-growing and conventional broiler flocks produced in the Netherlands and their respective antibiotic use, 2014-2019 (Data from AVINED (2020) – indicating that conventional, fast-growing broilers are associated with higher antimicrobial use in this dataset.

Year / Broiler type	DDDA~	Percentage of flocks (%)	Percentage of flocks raised without antibiotics (%)
2014	17.13	100	70
Slower-growing*	4.90	5	95
Conventional	17.83	95	67
2015	14.20	100	74
Slower-growing*	3.60	11	94
Conventional	15.56	89	70
2016	10.62	100	79
Slower-growing*	4.01	27	93
Conventional	13.11	73	72
2017	10.30	100	79
Slower-growing*	4.66	35	91
Conventional	13.37	65	71
2018	10.02	100	78
Slower-growing*	3.75	35	91
Conventional	13.42	65	69
2019	9.56	100	80
Slower-growing*	2.24	36	94
Conventional	13.70	64	70

~ DDDA = the defined daily dose animal, the standard unit of measurement for antibiotic use in the Netherlands. It is calculated by dividing the total number of treatable kilograms in the population for a specific year, by the average number of kilograms of animal in the population.
* The slower growing varieties are Hubbard JA87, Hubbard JA57, Ranger Classic (formerly Ross Ranger), Rowan Ranger; the Hubbard breeds have the largest market share.

2.3.2 Animal AMU and AMR

As the previous section described, antibiotic use is now a common feature within modern agricultural settings. Usage in these settings can be categorised by reason for treatment: therapeutic use involves the antibiotic treatment of an individual or a group of animals showing clinical signs of an infectious disease. Metaphylactic use comprises antibiotic administration to a group of animals containing sick and healthy animals (presumed to be infected), to minimise or resolve clinical signs and to prevent further spread of the disease. Prophylaxis is the administration of an antibiotic to an individual or a group of animals at risk of acquiring a specific infection, or in a situation where infectious disease is likely to occur if the drug is not administered. Finally, growth promotion, implemented in some jurisdictions, means

the administration of antimicrobial agents to animals only to increase the rate of weight gain or the efficiency of feed utilisation. (WOAH, 20122b)

There is a general scientific consensus that the introduction and continued use of antimicrobials in animals can favour the emergence of AMR, with human health consequences (ECDC *et al.*, 2017; Tang *et al.*, 2017). The causal pathway of this association has four steps: (a) the emergence of resistant bacteria or genetic determinants as a result of the antimicrobial use in animals; (b) the subsequent transmission of resistant bacteria or genetic determinants from animals to humans via direct contact, the food chain, and the environment; (c) the colonisation of humans with a bacteria possessing resistance of animal-origin; and (d) clinical impact on human health due to bacteria possessing resistance of animal-origin, including increased incidence and severity of infection leading to bloodstream infections, treatment failure, prolonged duration of illness, and mortality (Heuer *et al.*, 2009). Many studies provide evidence to support single or multiple steps in this causal pathway, for example Alexander *et al.* (2008), Aarestrup and Carstensen (1998), Levy *et al.*, (1976), Threlfall *et al.* (1997), Tacket *et al.* (1985), Vieira *et al.* (2011), and Hummel *et al.* (1986). However, there is also a growing evidence base from landmark studies that evidence the whole pathway, from AMU in animals to human disease.

In one such study, Tang *et al.* (2017) conducted a meta-analysis to assess the effect of interventions that restricted AMU in food-producing animals, on the prevalence of AMR in animals and humans. The authors found that restricting animal AMU reduced the prevalence of antibiotic-resistant bacteria in animals by 10-15%, and multidrug-resistant bacteria by 24–32%. Likewise, the pooled prevalence of antibiotic resistant bacteria in humans was 24% lower in the groups that restricted AMU in farmed animals compared to control groups, with a stronger association observed for people in direct contact with farmed species (Aidara-Kane *et al.*, 2018).

A second study of the same year found that the consumption of several antibiotic agents by farmed species in countries across the European Union (EU) was associated with the presence of antimicrobial resistant bacteria in animals, as well as human disease. Specifically, the ECDC *et al.* (2017) found associations between the

consumption of quinolones in farmed animals and the occurrence of fluoroquinolone resistance in invasive *E. coli, Salmonella* spp., and *C. jejuni* from humans. Correlations between macrolide consumption in animals and the occurrence of resistance to macrolides in *C. coli* and *C. jejuni* from humans were also statistically significant. The report highlights marked differences in associations between AMU and the occurrence of resistance depending on the antibiotic-bacteria combination, emphasising the propensity (for example) for *Campylobacter* to develop fluoroquinolone resistance (ECDC *et al.*, 2017).

Although this body of evidence points towards a causal relationship between AMU in farmed species and antimicrobial resistant infections with human health consequences, it appears that this relationship is complex and variable in its strength of association, depending on the antibiotics used, bacteria in question, and other poorly-understood factors. Some studies bring to light production system attributes that may increase the likelihood of resistant or multi-drug resistant bacterial shedding, such as the feeding of grain-based diets compared to silage-based diets in feedlot steers (Alexander *et al.*, 2008), and the rearing of dairy calves in dedicated calf-rearing facilities compared to on dairy farms (Berge *et al.*, 2005). Such studies suggest that efforts to reduce AMR risk should address not only AMU, but also a suite of other surrounding risk factors impacting animal wellbeing and the microbiome.

Furthermore, AMU is not a necessary nor sufficient cause of AMR, as explained in the model of epidemiological causation (Hoelzer *et al.*, 2017), but is a *probabilistic* cause of AMR (Parascandola and Weed, 2001). Firstly, antimicrobial pressure is not a *necessary* condition for the emergence of AMR, as indicated by the emergence of resistance determinant bacterial penicillinase in 1940, several years prior to the introduction of therapeutic penicillin (Abraham and Chain, 1940). Secondly, the presence of antibiotics is not *sufficient* to cause AMR, with many studies demonstrating an absence of resistance determinants despite antibiotic exposure, and in some cases, unexpected *reductions* in resistance to certain antibiotics following AMU (Benedict *et al.*, 2015).

Owing to these complexities, it is unfeasible to accurately identify the attributable fraction of bacteria possessing resistance from animal sources (FAO *et al.*, 2003), in part due to the bidirectional flow of genetic determinants of drug resistance between human and animal pathogens (Innes *et al.*, 2019). However, the Center for Disease Control and Prevention (CDC) estimate that one in five antimicrobial resistant bacterial infections is linked to food or animals (CDC, 2013), and Collignon *et al.* (2013) estimate that 1,518 additional deaths and an increase of 67,236 days of hospital admissions in the EU result from cephalosporin and other antimicrobial drug use in poultry. In addition, the societal externality cost of farmed animal AMU has been estimated by Innes *et al.* (2019) at US$1,500 per kilogram of fluoroquinolones administered in US broiler production. It can be concluded that, for many antibiotic-bacteria combinations, animal antibiotic use *increases the probability* that AMR will arise, presenting public health risks.

2.3.3 Animal and ecosystem impacts of AMU and AMR

So far, the AMU discussion in this chapter has focused on the *public health* risk of AMR. However, there is an emerging discourse amongst international institutions and the scientific community that highlights the impacts of farmed animal antibiotic use *beyond* human health and financial costs, to animal welfare and environmental externalities. The animal welfare dimensions of AMR have been highlighted by several studies, reporting cases of AMR associated with treatment failure in companion animals, horses, and food animals (Bengtsson and Greko, 2014; Gilbertie *et al.*, 2018). Resistant infections in animals can lead to greater overall antimicrobial exposure compared to cases responding to therapy (Booker and Lubbers, 2020), as well as negative social and economic consequences for the owners of the animals and the affected premises (Bengtsson and Greko, 2014). A World Bank report suggested that AMR in animals would reduce farmed animal production over time due to untreatable disease, with a more pronounced impact in lower- and middle-income countries (The World Bank, 2017).

In terms of environmental impacts, the risks of antibiotic residues and resistance to ecosystems have been highlighted by the UN Environment Programme (UNEP) in

their 2023 report 'Bracing for Superbugs' (UNEP, 2023). Many studies portray environmental compartments and wildlife species as 'reservoirs' and 'vectors' of AMR (Carroll *et al.*, 2015; Radhouani *et al.*, 2014), with environmental microbes harbouring and exchanging resistance characteristics following contact with bacteria and antibiotic residues discharged by human activity (UNEP, 2017). Indeed, diffuse environmental pollution with antibiotics and AMR determinants arises from human and animal AMU, with up to 80% of human antibiotics released in effluents (UNEP, 2017), and residues and resistant bacteria discharged in manure and agricultural run-off (Sarmah *et al.*, 2006; Kivits *et al.*, 2018). Anthropogenic sources also include use of antibiotics in aquaculture, with up to 80% lost to the marine environment (Cabello *et al.*, 2013), and in leachate from pharmaceutical waste disposal (Larsson, 2014b).

Although the *public health* consequences of acquiring resistant infections from the environmental resistome[14] are well researched (e.g., Finley *et al.*, 2013; Leonard *et al.*, 2015), there is less clarity around the impacts of antibiotic residues and AMR on ecosystem health and functionality (Kümmerer, 2004) and wild animal welfare. However, research by Sarmah *et al.* (2006) indicates that antibiotic residue toxicity affects multiple aquatic organisms, bacteria, macro-invertebrates, and plants. Blanco *et al.* (2020) warn of the impacts of intensive agriculture on the wildlife resistome including the microbiota of vultures, in which multi-drug resistance has been detected and attributed to their scavenging on the carcasses of medicated farmed animals. The environmental impacts of AMU and AMR are discussed in greater detail in Chapter 4.

2.3.4 Current levels of AMU in agriculture

With a growing understanding of the association between farmed animal AMU and its public health impacts, the UK's Swann Committee recommended restricting the use of antibiotic growth promoters in 1969. European bans on the use of specific antibiotics as agricultural growth promoters came into force from 1972, and Sweden

[14] The 'resistome' is the collection of natural and anthropogenic resistance determinants that directly or indirectly contribute to AMR (Wright, 2010; You *et al.*, 2014).

became the first state to prohibit the use of all antibiotic growth promotion in 1986 (Kirchhelle, 2018). Similar bans followed in the UK and EU in 2006, and the European Parliament has since prohibited the routine prophylactic use of antibiotics in animals (Regulation (EU) 2019/6 of the European Parliament and of the Council of 11 December 2018 on Veterinary Medicinal Products, 2018).

Against a backdrop of a predicted 67% increase in total AMU in tonnes for farmed animals between 2010 and 2030, attributed to growing populations and shifting production practices (Van Boeckel *et al.*, 2015), global AMU *per unit of animal biomass* (mg/kg) has reportedly been declining in recent years. The most recent report from WOAH on AMU documents a 13% decrease between 2017 and 2019 at global level, from 111.45 mg/kg to 96.73 mg/kg (in data representing 65% of the global animal biomass), including a 15% decrease in Europe (WOAH, 2022a). Over the same time period in the UK (2017-2019), the Veterinary Medicines Directorate (VMD) reported a 5% decrease in use in food producing animals, but a 59% reduction between 2014 and 2022 (from 62.3 to 25.7 mg/kg; VMD, 2023b). Although antibiotic use in crop production is observed in many countries, particularly in the rice and fruit sectors, it represents a relatively small proportion of total global antibiotic use (Taylor and Reeder, 2020) compared to use in the human and animal sectors.

Notwithstanding this important progress in antimicrobial stewardship in the UK and other regions, a total of 706 tonnes of antibiotic active ingredients were dispensed in 2019 in the UK for use in people and animals (32% of this was attributed to animal use; VMD, 2023a). Antibiotic use supporting human activity therefore remains a significant driver of AMR with human and animal health and wellbeing consequences, and source of diffuse environmental pollution with potential ecological impacts.

2.3.5 The economics of farmed animal antibiotic use

The previous sections have reflected on the co-evolution of antibiotic resources and existing agricultural systems, and the resultant use of antibiotics as inputs to support modern farmed animal production practices. In economics terms, farmed animals

and antibiotics are forms of (modified) natural capital, that are converted into both private goods (e.g., food, and other animal-source commodities) and public goods (e.g., antimicrobial efficacy, under systems of antimicrobial stewardship), from which human use value is derived. Antibiotics can be considered as *semi-renewable* resources, based on the propensity for *some* resistant bacteria to recover their susceptibility to an antibiotic once it is no longer exposed to the agent, and for *other* resistance determinants to persist in their hosts even after the selection pressure has been withdrawn[15] (Marshall and Levy, 2011; Hoelzer *et al.*, 2017).

In the process of producing food and other animal-source commodities from these resources, negative externalities arise as AMR, diffuse pollution with pharmaceutical residues and AMR determinants, and animal welfare harms. Considering the private use decision is not held accountable for these wider social costs (Moran, 2019), the overuse of animal antibiotics and AMR denote market failure.

2.3.6 Antibiotics and sustainability

Despite growing recognition of the human, animal, and environmental health risks posed by AMU and AMR, international policies, governance, and global intersectoral action remain lacking (Jasovský *et al.*, 2016). Increasing levels of AMR directly threaten the attainment of the SDGs, in particular 'Good health and wellbeing' (Gajdács *et al.*, 2021); however, the issue is not explicitly featured in the goals, nor is it included in the UN's SDG targets within the updated '2030 Agenda for Sustainable Development' (UN, 2015b). However, it is mentioned once in the latter document, which states: "*[W]e will equally accelerate the pace of progress made in fighting malaria, HIV/AIDS, tuberculosis, hepatitis, Ebola and other communicable diseases and epidemics, including by addressing growing antimicrobial resistance and the problem of unattended diseases affecting developing countries".*

Despite its limited inclusion in sustainability frameworks, action on AMR as an isolated challenge is gaining traction through voluntary initiatives, spearheaded by

[15] This appears to depend on the fitness cost associated with harbouring the resistance genes, or the stability of the plasmid in the host.

global institutions. The World Health Assembly adopted a non-legally binding Global Action Plan on AMR in 2015, reflecting a global consensus that *"antimicrobial resistance poses a profound threat to human health"* (World Health Organization (WHO), 2015). National multisectoral AMR action plans have been adopted by an increasing number of countries, from 4% (6/159) to 20% (32/163) between 2017 and 2021 (FAO, UNEP, WHO, 2022a). A group of multilateral agencies consisting of the WHO, FAO, WOAH, and UNEP have also published a Strategic Framework on AMR, reflecting their joint work to advance a One Health response to the problem (FAO *et al.*, 2022b). Their overarching goal is to *"to preserve antimicrobial efficacy and ensure sustainable and equitable access to antimicrobials for responsible and prudent use in human, animal and plant health, contributing to achieving the Sustainable Development Goals (SDGs)"*.

Antimicrobial resistance (AMR) is also the subject of a growing number of government and private sector initiatives, with programmes to monitor and reduce animal AMU in motion across the European agricultural sectors, such as the Yellow Card scheme in Denmark and the Responsible Use of Medicines in Agriculture Alliance (RUMA) Targets Task Force in the UK (Speksnijder, *et al.*, 2015; Lopes Antunes and Jensen, 2020; RUMA, 2020). In the UK Government's O'Neill Report (O'Neill, 2016), AMR is framed as *"one of the biggest health threats that mankind faces now and in the coming decades"*. Within the private sector, many food service companies, retailers, and food brands have published antimicrobial stewardship policies, and publicly report data on the usage of antibiotics in their farmed animal supply chains (e.g., ASDA, 2018; Marks and Spencer, 2017; McDonald's Corporation, 2017; Sainsburys, 2019; Tesco, 2019) - actions that are advocated by several non-governmental organisations (NGOs) and investor groups (Share Action, 2016; Alliance to Save Our Antibiotics (ASOA), 2020, 2021; Amos *et al.*, 2021; FAIRR, 2021)

Together with the animal antibiotic use reductions documented for many regions (VMD, 2023b; WOAH, 2022a), these programmes signify marked global progress on AMR and its firm establishment within the One Health agenda. However, the AMR challenge is primarily contextualised as a threat to antibiotic efficacy, anthropocentric health objectives, and sustainable development. Programmes appear particularly

attentive to antimicrobial stewardship interventions to the extent that they align with human interests (i.e., tackling infectious disease), running the risk of deprioritising root-cause, preventative actions that promote the wellbeing of non-human animals and ecosystems. For example, antimicrobial stewardship reports and plans from multilateral agencies (WHO, 2015; FAO *et al.*, 2022b) do not include interventions to minimise the impacts of antibiotic residues and resistance determinants on non-target organisms, or to incentivise husbandry practices with co-benefits for animal welfare (including mental wellbeing).

It is therefore supposed that the majority of global farmed animal AMU and existing stewardship efforts are primarily driven by anthropocentric motives. As a result, AMU in many farmed animal settings is facilitating and optimising the use value derived from animals for current generations, meanwhile producing harmful externalities and eroding public goods (i.e., antimicrobial efficacy and biodiversity) that will impact future generations and non-human species.

2.4 Animal welfare and AMU in the Anthropocene

These challenges of animal welfare and antimicrobial stewardship in the context of farmed animal production share several common characteristics. Firstly, both issues are of growing importance to society, and can be accommodated in both the ‘weak’ and ‘strong’ sustainability paradigms, when such externalities are effectively accounted for. However, animal welfare and antimicrobial stewardship have traditionally been neglected from the sustainability discourse and frameworks, pointing to a science-policy gap: they are absent from the UN SDGs (Schapper and Bliss, 2023), and planetary boundaries have been neither defined nor adopted for the problems, despite calls and proposals by research groups (Jørgensen *et al.*, 2018; Gupta *et al.*, 2023). Both problems are emblematic of anthropocentric human-animal relations, for which regulations have failed to keep pace with scientific advancements and public sentiment. Although subject to baseline legislation in the UK, free markets are unable to accurately internalise the impacts of poor animal welfare and antibiotic residues and resistance, beyond their alignment with human

interests and development. Hence, these issues are similarly indicative of market failure, representing harmful externalities generated in the process of converting commodified animals and antibiotics into private and public goods. These ideas are presented in Figure 2.

In conclusion, animal welfare and antimicrobial stewardship are situated within the sustainability agenda, but associated challenges in the farmed animal context arise as externalities of anthropocentric human-animal relations. They are exemplars of sustainability challenges that may be solved partly by the market but also by embracing an ecological approach that dismantles inequities inherent in market-driven resource allocation. Insights can be gleaned from sustainability thinking that has evolved since the Brundtland Report, in the ecological economics sphere. As briefly described previously, ecological sustainability responds to scientific assessments of rapidly degrading ecosystems by promoting the efficient, equitable, and sustainable allocation of scarce and finite resources, including ‘natural’ and ‘social’ capital (Borland and Lindgreen, 2013). It considers humans to be part of a larger ecosystem and not separate from it (Costanza, 2008), and looks beyond neoclassical economics and its focus on Gross Domestic Product (GDP) as the metric of human progress (Stuchtey *et al.*, 2016), to a broad consideration of wellbeing across species and generations, dependent on the regeneration of Earth’s resources (Borland and Lindgreen, 2013). Social justice and flourishing are being incorporated into the planetary boundaries concept (Rockström *et al.*, 2023), representing a potential entry point for the similar consideration of animal wellbeing. Such thinking could shape a new era of policy making around the human treatment of domesticated and wild animals, informing decisions based on balanced evaluations of multiple sustainability objectives, and regenerating capital stocks across the One Health domains.

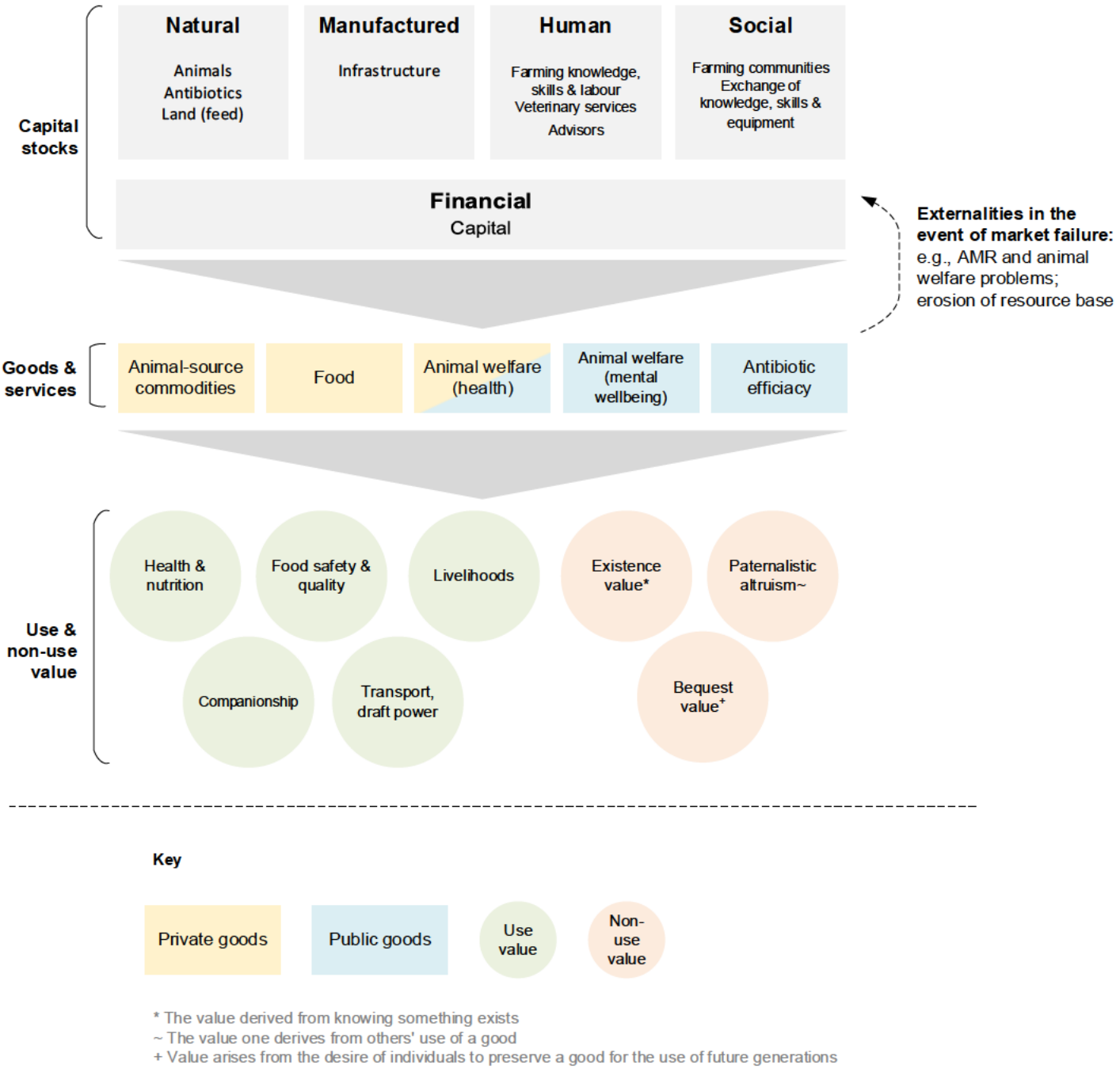

Figure 2: Illustration depicting the flow of goods and services from capital stocks, and the use/non-use value of farmed animals. In the event of market failure, externalities are generated in the form of animal welfare problems and AMR. The definitions of non-use value are derived from Lagerkvist *et al.* (2011).

2.5 The role of veterinary professionals

The current chapter addresses the first research question, and concludes that animal welfare and antimicrobial stewardship *are* sustainability issues, but are subject to public and private policy gaps in the UK, for example in relation to farmed animals. Focussing on the subsequent research questions, the proceeding chapters explore the roles, barriers, and actions for relevant stakeholders to integrate animal welfare and antimicrobial stewardship into the sustainability agenda. The next chapter focusses on veterinary professionals.

Working at the human-animal-environment interface, veterinary professionals have a crucial role, duty, and opportunity to advance the sustainability agenda across the One Health domains. Indeed, The UK's Royal College of Veterinary Surgeons (RCVS) Code of Professional Conduct states: *"Veterinary surgeons must seek to ensure the protection of public health and animal health and welfare and must consider the impact of their actions on the environment."* (RCVS, no date, a). Leveraging their desire to contribute to the sustainability agenda (British Veterinary Association (BVA), 2019d), and their trusted position amongst the UK public (RCVS, 2019), veterinary professionals hold opportunities to identify and mitigate the externalities of veterinary service provision (e.g., the ecological impacts of medicine residues and resistance determinants (Perkins *et al.*, 2021), and enhance and regenerate the resources and public goods that can arise from animal care and husbandry (e.g., animal welfare, biodiversity). In particular, animal welfare and antimicrobial use represent sustainability issues that veterinary professionals are mandated to support, advocate, and gatekeep.

Exploring a research gap in this area, Chapter 3 identifies the sustainability policies and practices enacted in a sample of clinical veterinary centres in the UK and Republic of Ireland, and the provision of veterinary advice to animal keepers on sustainable husbandry and management. It responds to research questions 2, 3, and 4, by exploring the veterinary role in sustainability including their policy approach to animal welfare and antimicrobial stewardship, barriers to establishing relevant

policies and practices, and the actions that could leverage the veterinary role in sustainability.

3. Sustainability policies and practises at veterinary centres in the United Kingdom and Republic of Ireland

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Abstract

Background: Veterinary professionals operate at the human-animal-environment interface and are concerned about sustainability issues. This study examined the extent to which sustainability is represented in policy and enacted in veterinary practice settings, as reported by practice representatives.

Methods: An online survey was completed by 392 veterinary centre representatives in the UK and Republic of Ireland, to identify existing policies and practises around the environmental impacts of veterinary services and animal husbandry, responsible medicine use, animal welfare and social wellbeing.

Results: A minority of respondents were aware of an environmental policy at their practice (17%, 68/392). Many others were undertaking waste reduction initiatives, but wider environmental interventions were infrequently reported. The majority were aware of medicine stewardship and animal welfare policies or guidelines, but a

minority reported social wellbeing policies (40%, 117/289) and the provision of advice to clients on the environmental impacts of animal husbandry (31%, 92/300).

Conclusion: Results depict a value-action gap between the concern of veterinary professionals towards sustainability, and the policies and practises at their workplaces. Building on progress in the sector, wider adoption of comprehensive policies and practises, with guidance, could enhance veterinary contributions to the sustainability agenda, in particular to mitigate the environmental externalities of veterinary services and animal care, and ensure safe, fair and inclusive workplaces.

Limitations: The bias arising from the small convenience sample of practice representatives, and potential discrepancies between the claims of survey respondents and their practices' policies and activities, are acknowledged.

3.1 Introduction

Humanity is currently facing a multitude of complex and pressing sustainability challenges, including climate change (Costello *et al.*, 2009; Balasubramanian, 2018), biodiversity loss (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2019), public health epidemics (Taylor *et al.*, 2001; O'Neill, 2016), social inequity (Chancel *et al.*, 2022) and animal welfare problems (Rioja-Lang *et al.*, 2020). The need to address these issues has driven many disciplines to conceptualise and define sustainability, based on a spectrum of ideologies regarding the relative value of humans within the earth's ecosystem. At one end, the neoclassic 'technocentric' paradigm assumes that the earth's resources are available for exploitation and technological solutions will facilitate continued and unfettered growth and consumption (Lomborg, 2001; Borland and Lindgreen, 2013). At the other, 'ecocentrism' considers nature to hold intrinsic value, with humans, animals and plants possessing equal rights to exist (Allen *et al.*, 2019; Lovelock, 2000; Purser *et al.*, 1995).

The current dominant paradigm lies somewhere along this continuum, and is articulated in the widely adopted definition of sustainable development from the UN's Brundtland Report: "*development which meets the needs of current generations without compromising the ability of future generations to meet their own needs*" (WCED, 1987). It recognises the value of ecological integrity, but asserts that natural capital can, in some circumstances, be substituted for man-made capitals (Buriti, 2018). Such anthropocentric viewpoints prioritise human development over the needs of all other species, whilst generating and detaching various sub-disciplines, such as environmental management (Purser *et al.*, 1995; Porritt, 2012). Following this philosophy, many organisations address sustainability concerns by monitoring and controlling the environmental impact of 'business-as-usual' processes, framed as working 'more efficiently', by accelerating innovation to reduce the utilisation of inputs whilst maintaining levels of consumption (Allen *et al.*, 2019).

The Brundtland definition succeeded in acknowledging the biosphere's finite resources (WCED, 1987) and brought intergenerational ethics of resource use into sharp focus (Naudé, 2017). However, definitions have since evolved towards an ecological sustainability paradigm, which places inherent value on the ecosystem and supports interspecies and intergenerational justice. In the UN's updated SDG Agenda for 2030 (UN, 2015b), 'sustainability' includes environmental, human, *and* animal welfare domains in line with the One Health concept (OHHLEP, 2020), and a recent development is the recognition of ultimate planetary boundaries that define a safe operating space for humanity (Steffen *et al.*, 2015) and limits to "conventional" economic growth (Porritt, 2012).

3.1.1 Veterinary professionals and sustainability

Sustainability issues are often characterised as the depletion of resources, embodied in manufactured, human, social, and natural capital. The public and private goods and services flowing from these capital stocks generate a range of use and non-use values (i.e., human wellbeing), and in some cases, harmful social and environmental impacts (externalities) that impose costs to society.

Veterinary professionals, including veterinary scientists and allied professionals (BVA, 2019a), operate at the human-animal-environment interface (RCVS and BVA, 2015) and are involved in the delivery of public and private goods and services (Éloit, 2012) that generate both positive externalities (Stewart *et al.*, 2005; Éloit, 2012; Romero, 2018) and negative externalities (Platt *et al.*, 2012; Lloyd, 2017; Tang *et al.*, 2017; Koytcheva *et al.*, 2021). Veterinary scientists have a core mandate to protect the welfare of animals under their care (RCVS, no date, a), and in a minority of jurisdictions, a professional duty to consider their impacts on public health and the environment, including in the UK, the Republic of Ireland, and Canada (Canadian Veterinary Medical Association, 2018; RCVS, no date, a; Veterinary Council of Ireland, 2021). The World Veterinary Association (WVA) acknowledges that *"Veterinarians…have a responsibility to protect ecosystem health"* (WVA, 2020), in alignment with an ecological sustainability ideology and the One Health paradigm, which aims to balance and optimise the health of people, animals, and ecosystems (OHHLEP, 2020). Supportive of their multiple obligations, Stephen and colleagues (Stephen *et al.*, 2019) envisage "*veterinary medicine [as] a steward of healthy animal populations and biodiversity and the benefits they bring ecosystems and society*", and 89% of UK veterinary surgeons wish to play a more active role in the sustainability agenda (BVA, 2019d).

To operationalise the responsibility and concern of veterinary professionals for sustainability, frameworks have been created by organisations including the RCVS (Practice Standards Scheme (PSS) for Sustainability; RCVS, no date, b), Investors in the Environment (IIE, 2019), and Vet Sustain. Considering all three of the One Health domains and using the UN SDGs as a blueprint, Vet Sustain devised a set of 'veterinary sustainability goals' (VSGs) (Vet Sustain, 2020) (see Table 1), mapped to current and potential actions by veterinary professionals.

Many of the day-to-day actions of veterinary professionals listed in Table 1 such as the delivery of clinical and public health services are extensively documented (WOAH, 2022b) and can contribute directly to the VSGs/SDGs (e.g., Trevejo, 2009; Kelly *et al.*, 2014). However, other potential contributions such reducing the environmental impacts of veterinary services are characterised by a nascent body of literature (Jones and West, 2019; Kramer *et al.*, 2020; Pollard *et al.*, 2020; West and

Malalana, 2020; Alders *et al.*, 2021; Deluty *et al.*, 2021; Koytcheva *et al.*, 2021; Mair *et al.*, 2021; Schiavone *et al.*, 2022), individual cases of exemplary practice (Davies Veterinary Specialists, 2022), and a growing but fragmented movement of voluntary support, education, information, and labelling schemes. Such programmes include the involvement of professional bodies in environmental consortia (Paterson, no date), the appointment of sustainability specialists and publication of sustainability reports by practice groups (IVC Evidensia, 2021; Mars, 2021; VetPartners, 2021; CVS Group plc, 2022; Pets At Home Group plc, 2021), professional environmental training, guidance and self-assessments (Vet Sustain, 2021, 2022; BVA, 2022), undergraduate curriculum projects (Boyd *et al.*, 2020), environmental accreditation schemes (IIE, 2019; RCVS, no date, b), antibiotic stewardship training, awards and guidance (British Equine Veterinary Association (BEVA), no date; RCVS Knowledge, no date; British Small Animal Veterinary Association (BSAVA), 2018; BVA, 2019c), animal welfare accreditation schemes (International Cat Care, no date), workplace wellbeing guidelines and accreditations (RCVS, no date, b; BVA, 2020) and mental health support (Mind Matters, no date; VetLife, no date). A number of independent communities also work to promote sustainability (Vet Sustain, 2021), diversity and inclusion (British Veterinary Ethnicity and Diversity Society (BVEDS), 2021), women's empowerment (Veterinary Woman, 2022), veterinary wellbeing (WellVet, no date), fulfilling veterinary careers (Vets Stay Go Diversify (VSDG), 2019) and One Welfare (One Welfare CIC, 2022).

However, the extent to which potential veterinary contributions to sustainability are represented in veterinary centre operations is currently unknown. This study was conducted to identify existing sustainability policies and practises as reported by representatives of clinical veterinary centres in the UK and Republic of Ireland. 'Policy' in this context relates to those devised at veterinary centre-level to define intentions, objectives, or goals, as opposed to higher-level national or legal policy. The study also aimed to identify opportunities to enhance veterinary contributions to the sustainability agenda, with a focus on opportunities within clinical settings.

3.2 Materials and methods

The survey was devised by Vet Sustain in partnership with The Veterinary Defence Society (VDS), to identify veterinary clinic policies and practises around sustainability, according to contemporary definitions including human, animal, and environmental wellbeing. Vet Sustain is a social enterprise aiming to empower the veterinary profession to drive change for a more sustainable future, and VDS is the UK's largest provider of veterinary professional indemnity insurance, working to support and protect veterinary professionals, practices, and businesses.

In the absence of an established framework for assessing the sustainability of veterinary services across the One Health domains, the themes of the survey were scoped using a literature search to identify the roles played by veterinary professionals in contribution to the VSGs. The results are displayed in Table 4. To focus the survey, these roles were consolidated into: 1) environmental impacts of veterinary services; 2) responsible medicine use (antibiotics and parasiticides); 3) promoting animal welfare; 4) environmental impacts of animal husbandry; and 5) promoting social wellbeing. The survey questions were then devised using several rounds of consultation with Vet Sustain and VDS representatives. The full survey can be found in the Supplementary Materials, and included a variety of open and closed questions relating to the role of the respondent, the type of veterinary practice they represented, policies or activities at their practices around the five key themes, and preferences for future training. Questions explored their awareness of legal requirements, examples of sustainability advice provided to animal owners, and their views on interventions to support sustainability at their workplace and in the veterinary sector, in order to inform the work of Vet Sustain and other interested parties.

Closed questions generated multiple choice, ranking or likert scale (Likert, 1932) responses. Throughout the survey, ‘policies’ were described as “*a business-wide, generally agreed set of principles that influence the working environment and culture*”, in order to capture both written and non-written policies and principles communicated by management. Respondents provided informed consent and were

offered the opportunity to remain anonymous, or share their contact details to be entered into a prize draw for a free book. Personal data were deleted as soon as the draw was complete.

The survey was distributed electronically to a sample of 4,947 VDS members that had opted to receive mailings, representing clinical veterinary centres in the UK and Republic of Ireland. The survey was also disseminated to 1,109 veterinary professionals in a Vet Sustain Mailchimp newsletter, and via Vet Sustain and VDS social media channels. This convenience sample using the VDS and Vet Sustain databases aimed to maximise participation from across the profession, considering the VDS' representation of the vast majority of UK veterinary practices. The survey was open between 21st April and 4th June 2021 and could be completed by *any member* of the veterinary centre team, reflecting their awareness of workplace policies and practises.

When more than one submission was received from the same practice site, one of the responses was randomly selected for inclusion by VDS, leaving 446 unique responses. Data were then anonymised and transferred to Vet Sustain in a password-protected Microsoft Excel® 2016 (Microsoft Corporation) database, cleaned, and 54 responses without answers to questions beyond role and practice type were removed, leaving 392 for analysis. Simple descriptive and qualitative analyses were performed, and categorical variables were described with frequency, percentages and 95% confidence intervals (CIs) for proportions. A content analysis approach was adopted for free-text responses, in which concepts were identified and categorised into common themes by the primary author and described with frequency. The number of responses to each question were specified as 'n' within the results. Following the survey, a selection of potential interventions was compiled by the authors that may address the gaps in policies and practises identified by the survey. This study received ethical approval from the RCVS Ethics Review Panel (Reference 2022-090-Oxtoby).

Table 4: The Veterinary Sustainability Goals, adapted from Vet Sustain (2020) in contribution to the UN SDGs (UN, 2015a), and relevant veterinary roles.

UN Sustainable Development Goals	*Veterinary Sustainability Goals (VSGs)*	*Veterinary roles to support the VSGs*
	**Diverse and abundant wildlife**	**Sustainable operating practices and circular/efficient resource use** (Jones and West, 2019; West and Malalana, 2020); **Owner education and farm consultancy for sustainable animal care** (Green *et al.*, 2011; Prentis, 2021); **Provision of undergraduate, postgraduate and specialist training and education** (RCVS and BVA, 2015) **Leadership and public advocacy** (The European College of Veterinary Public Health (ECVPH), no date; BVA, 2015, 2019b).
	**A Good Life for Animals**	**Ensuring the welfare of animals under veterinary care** (Wensley *et al.*, 2020); **The delivery of veterinary services for animal health, welfare, and production** (WOAH, 2022b); **Responsible medicine use** BVA, 2019c; Herrero-Villar *et al.*, 2020; BVA, BSAVA and British Veterinary Zoological Society (BVZS), 2021); **Product innovation, development, and marketing** (Robinson *et al.*, 2019; Thompson and Ahmadi, 2018); **Provision of undergraduate, postgraduate and specialist training and education** (RCVS and BVA, 2015); **Leadership and public advocacy** (ECVPH, no date; BVA, 2015, 2019b).
	**Net Zero Warming**	**Sustainable operating practices and circular/efficient resource use** (Jones and West, 2019; West and Malalana, 2020); **Owner education and farm consultancy for sustainable animal care** (Green *et al.*, 2011; Prentis, 2021); **Provision of undergraduate, postgraduate and specialist training and education** (RCVS and BVA, 2015); **Leadership and public advocacy** (ECVPH, no date; BVA, 2015, 2019b).

	**Health and Happiness**	**Public health and food safety** (Tang *et al.*, 2017; van Herten and Meijboom, 2019); **Disease surveillance and control** (Thrusfield, 2007); **Responsible medicine use** (BVA, 2019c; Herrero-Villar *et al.*, 2020; BVA, BSAVA and BVZA, 2021); **Social interventions, such as green and social prescriptions and recognising and responding to signs of abuse** (Boyden *et al.*, no date; Barton and Pretty, 2010); **Workplace practises for equality and wellbeing in the veterinary team** (Mind Matters, no date; Begeny *et al.*, 2020; BVA, 2020); **Provision of undergraduate, postgraduate and specialist training and education** (RCVS and BVA, 2015); **Leadership and public advocacy** (ECVPH, no date; BVA, 2015, 2019b).
	**A No-Waste Society**	**Sustainable operating practices and circular/efficient resource use** (Jones and West, 2019; West and Malalana, 2020); **Responsible medicine use** (BVA, 2019c; Herrero-Villar *et al.*, 2020; BVA, BSAVA and BVZS, 2021); **Owner education and farm consultancy for sustainable animal care** (Green *et al.*, 2011; Prentis, 2021); **Provision of undergraduate, postgraduate and specialist training and education** (RCVS and BVA, 2015); **Leadership and public advocacy** (ECVPH, no date; BVA, 2015, 2019b).
	**Enough Clean Water for All**	**Responsible medicine use** (BVA, 2019c; Herrero-Villar *et al.*, 2020; BVA, BSAVA and BVZS, 2021); **Sustainable operating practices and circular/efficient resource use** (Jones and West, 2019; West and Malalana, 2020); **Owner education and farm consultancy for sustainable animal care** (Green *et al.*, 2011; Prentis, 2021); **Provision of undergraduate, postgraduate and specialist training and education** (RCVS and BVA, 2015); **Leadership and public advocacy** (ECVPH, no date; BVA, 2015, 2019b).

3.3 Results

The roles of respondents are shown in Table 5. The majority of respondents (66%, 257/392) were from small animal and exotics practices, 14% (54/392) from mixed practices, 9% (34/392) from equine practices and 8% (30/392) from farm animal practices. Of those specifying practice type, respondents worked at first opinion practices (33%, 131/392), specialist referral clinics (9%, 35/392), charity clinics (3%, 13/392), teaching institutions (3%, 10/392), industry (2%, 8/392) and government (2%, 7/392), with some representing multiple practice types.

Table 5: Number and proportion of survey respondents, based on role in the veterinary practice (n = 392). Some respondents held multiple roles.

Role in Practice	Number	Proportion
Veterinary surgeon	288	0.73
Practice owner or partner	67	0.17
Clinical director, director or other member of the leadership team	56	0.14
Veterinary nurse	52	0.13
Practice manager	25	0.06
Trainee veterinary nurse	4	0.01
Receptionist	4	0.01
Other	4	0.01
Animal assistant	3	0.01
Veterinary student	2	0.01
Technician	0	0.00

3.3.1 Environmental impacts of veterinary services

A minority of the 392 respondents (17%, 68/392; 95% CI=0.14-0.21) reported to have an environmental policy at their practice, 53% (208/392; 95% CI=0.48-0.58) did not, and 30% (116/392; 95% CI=0.25-0.34) didn't know. Of those that did claim to have an environmental policy, 55 selected the items it included from a list, as shown in Table 6. The majority of respondents selecting the contents of their environmental policy (62%, 34/55; 95% CI=0.49-0.75) listed at least seven elements.

Table 6: Elements included in veterinary practice environmental policies, by number and proportion of survey respondents with 95% confidence intervals (CIs) (n = 55).

Response	Number	Proportion	(95% CIs)
Recycling and waste segregation	41	0.75	(0.63 - 0.86)
Reduction in usage of packaging and single-use items	33	0.60	(0.47 - 0.73)
Energy usage	32	0.58	(0.45 - 0.71)
Paper usage (source, use, disposal)	29	0.53	(0.40 - 0.66)
Staff engagement	26	0.47	(0.34 - 0.60)
Anaesthetic gases	25	0.45	(0.32 - 0.59)
Water usage	22	0.40	(0.27 - 0.53)
Transport (e.g., commuting, travel in company vehicles, supporting walking/cycling and use of public transport)	20	0.36	(0.24 - 0.49)
Procurement of supplies	20	0.36	(0.24 - 0.49)
Medicine use (waste reduction; ecotoxicity of antiparasitics)	20	0.36	(0.24 - 0.49)
On-site biodiversity and green spaces	20	0.36	(0.24 - 0.49)
Carbon footprint information	17	0.31	(0.19 - 0.43)
Legal compliance	16	0.29	(0.17 - 0.41)
Publicly available policy statement	14	0.25	(0.14 - 0.37)
Chemicals e.g., cleaning materials, sterilising fluids, radiography developers	12	0.22	(0.11 - 0.33)
Environmental building design and infrastructure	12	0.22	(0.11 - 0.33)
Community projects	12	0.22	(0.11 - 0.33)
Carbon offsetting	11	0.20	(0.09 - 0.31)
Monitoring and reporting	10	0.18	(0.08 - 0.28)
Client education	8	0.15	(0.05 - 0.24)
External accreditations	8	0.15	(0.05 - 0.24)
Don’t know	8	0.15	(0.05 - 0.24)
Food procurement and/or disposal	6	0.11	(0.03 - 0.19)
Preventive medicine	6	0.11	(0.03 - 0.19)
Other	1	0.02	(0.00 - 0.05)

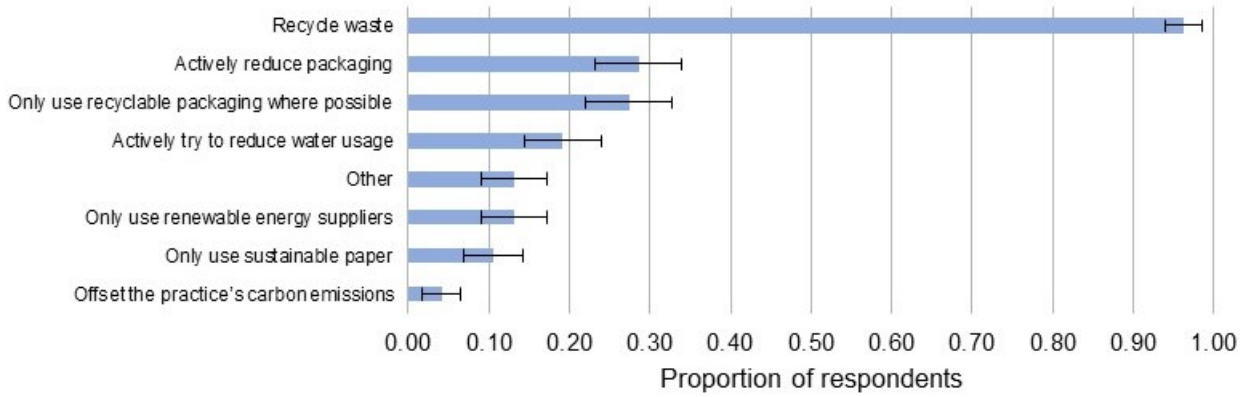

Figure 3: Actions by veterinary practices to support the environment, as reported by survey respondents, with 95% confidence intervals (n = 266).

Respondents that *did not* have a policy were offered the opportunity to select or specify any actions their practices undertook to support the environment, and the results are displayed in Figure 3. Amongst the "other" actions, small numbers of respondents reported that their practices were using electric vehicles (2%, 4/266; 95% CI=0.00-0.03), reducing energy usage (2%, 4/266; 95% CI=0.00-0.03), composting kitchen waste (2%, 4/266; 95% CI=0.00-0.03), using or installing solar panels (1%, 3/266; 95% CI=0.00-0.02), using specialist recycling for pet food and crisp packaging (1%, 3/266; 95% CI=0.00-0.02), and using reusable surgical hats/gowns (1%, 3/266; 95% CI=0.00-0.02).

When asked what measures would support their practices to adopt an environmental policy, 78% of 293 respondents (228/293; 95% CI=0.73-0.83) selected greater knowledge on sustainable solutions for veterinary practices. The majority of respondents that selected greater knowledge on sustainable solutions also requested standards and guidelines to follow (63%, 143/228; 95% CI=0.56-0.69). When asked how aware they were of legal and regulatory requirements relating to sustainability and their impact on veterinary practice, 50% (170/341; 95% CI=0.45-0.55) were not aware and 2% (6/341; 95% CI=0.00-0.03) were fully aware.

3.3.2 Responsible medicine use

Of 339 respondents, a majority of 72% (243/339; 95% CI=0.67-0.76) had a policy on antibiotic use and stewardship, 17% (59/339; 95% CI=0.13-0.21) did not, and 11% (37/339; 95% CI=0.08-0.14) didn't know. Analysing these by practice type, 74% (25/34; 95% CI=0.59-0.88) of representatives from equine and 73% (22/30; 95% CI=0.58-0.89) from farm animal practices reported having antibiotic stewardship policies, compared to 65% (167/257; 95% CI=0.59-0.71) of respondents from small animal and exotics and 54% (29/54; 95% CI=0.40-0.67) from mixed practices. The elements of antibiotic policies most frequently cited by 231 respondents are shown in Figure 4. Respondents that *did not* have a policy most frequently specified infection and hygiene procedures (71%, 59/83; 95% CI=0.61-0.81) as the actions their practices were undertaking around antibiotic stewardship. Of 93 respondents who specified what would support their practices in implementing an antibiotics policy, the highest percentage (66%, 61/93; 95% CI=0.56-0.75) selected standards, guidance, and frameworks to follow.

Of 321 respondents, 51% (165/321; 95% CI=0.46-0.57) reported having a policy on the use of medicines for parasite control at their practice, 35% (111/321; 95% CI=0.29-0.40) did not, and 14% (45/321; 95% CI=0.10-0.18) didn't know. The most frequently included policy elements cited (n=164) were treatment protocols and guidelines (88%, 145/164; 95% CI=0.84-0.93), guidelines on prophylactic use of parasiticides (62%, 101/164; 95% CI=0.54-0.69) and client education and compliance (60%, 98/164; 95% CI=0.52-0.67). Other responses included risk assessments for use in individual patients (37%, 61/164; 95% CI=0.30-0.45) and the requirement for pre-treatment diagnostic testing prior to prescribing (21%, 34/164; 95% CI=0.15-0.27).

The *actions* around parasiticide use specified by respondents that reported not to have a policy (n=99) are shown in Figure 5. Of 142 respondents without a policy, 66% (94/142; 95% CI=0.58-0.74) believed that standards, guidelines, and frameworks for practices to follow and 61% (87/142; 95% CI=0.53-0.69) felt that

clear demonstration of the benefits to public/animal health would support uptake of a parasite control policy at their practice.

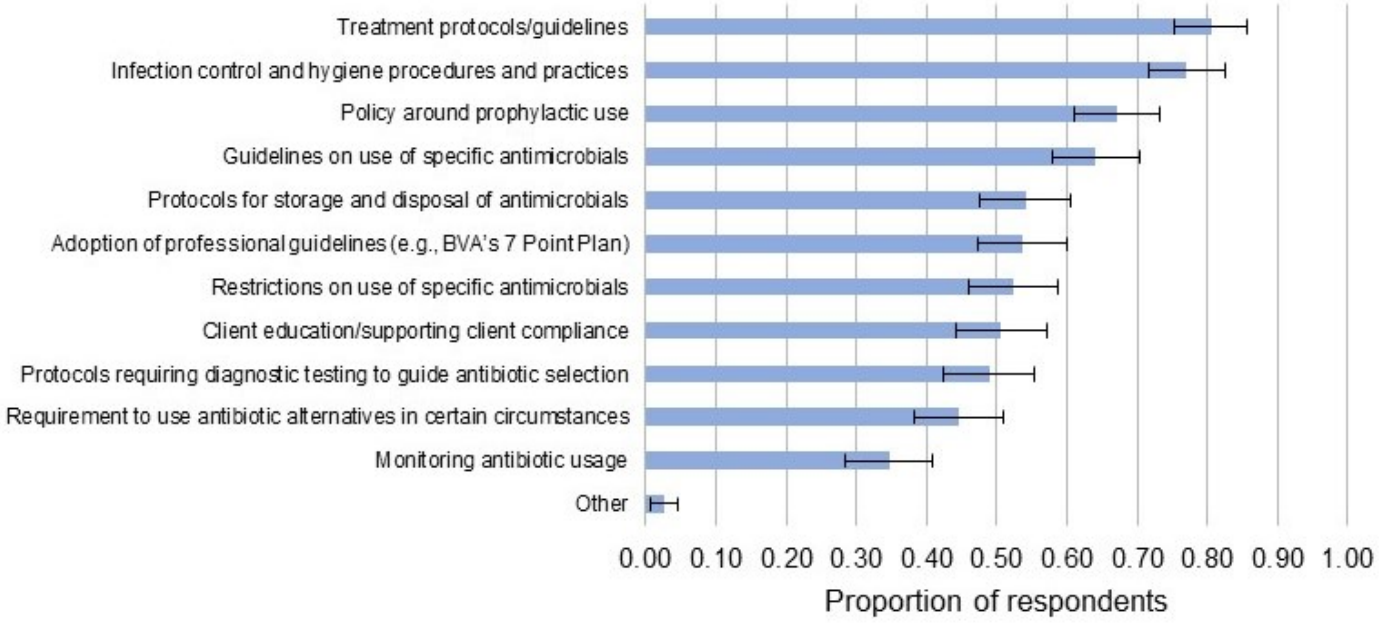

Figure 4: Elements included in veterinary practice antibiotic use and stewardship policies, according to veterinary practice representatives, with 95% confidence intervals (n = 231).

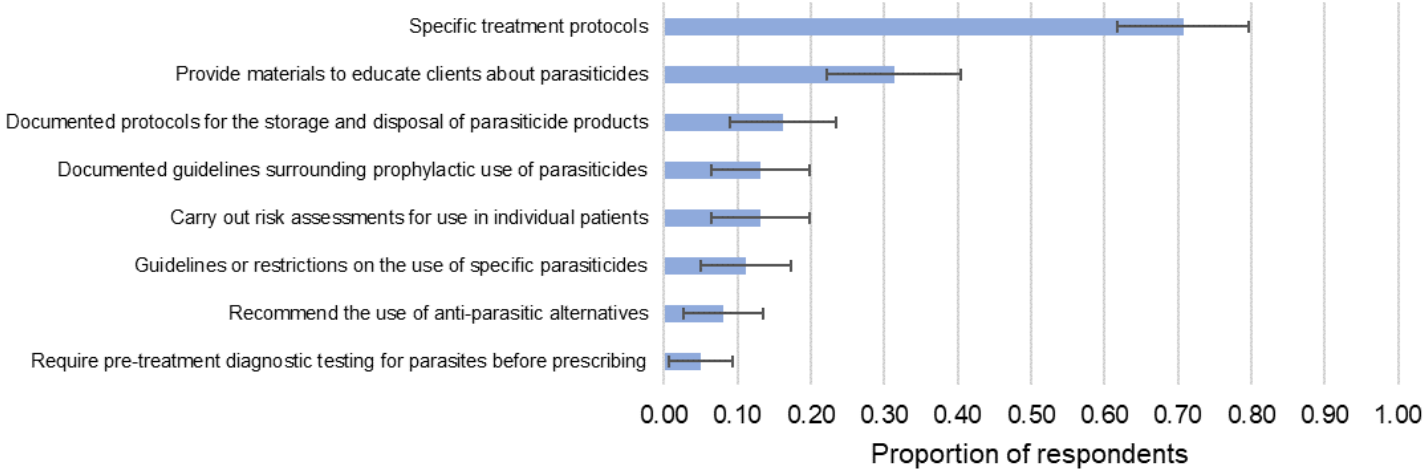

Figure 5: Actions taken by veterinary centres on the use of medicines for parasite control, as reported by survey respondents with 95% confidence intervals (n=99).

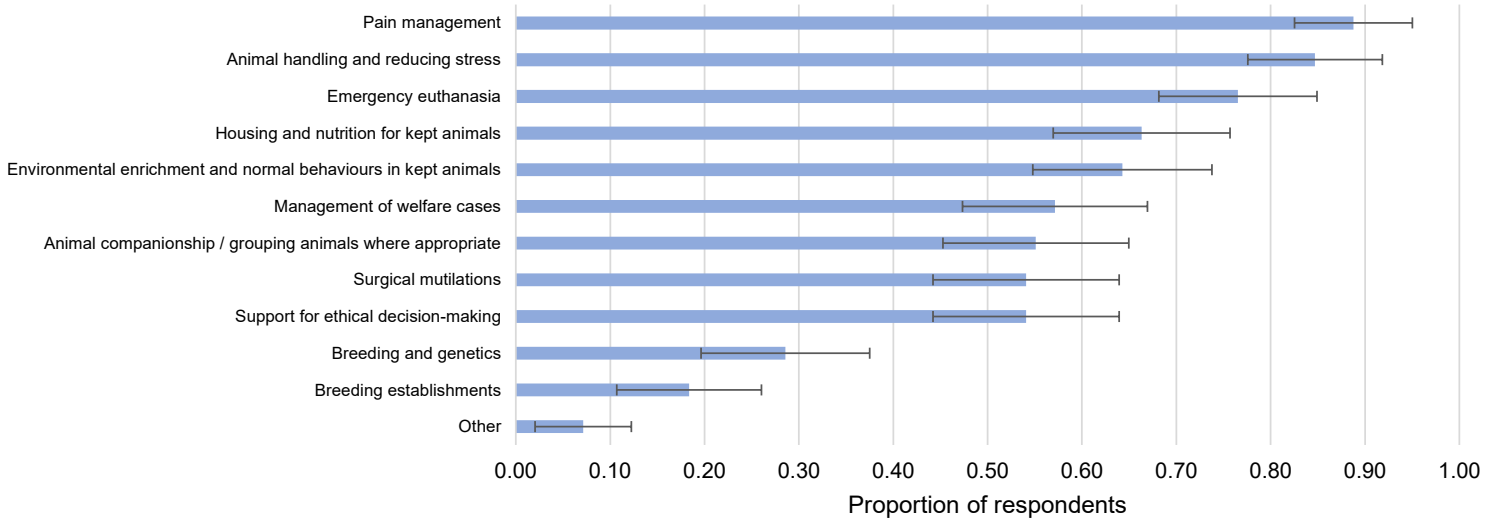

Figure 6: Aspects included in veterinary practice animal welfare policies, as reported by survey respondents with 95% confidence intervals (n = 98).

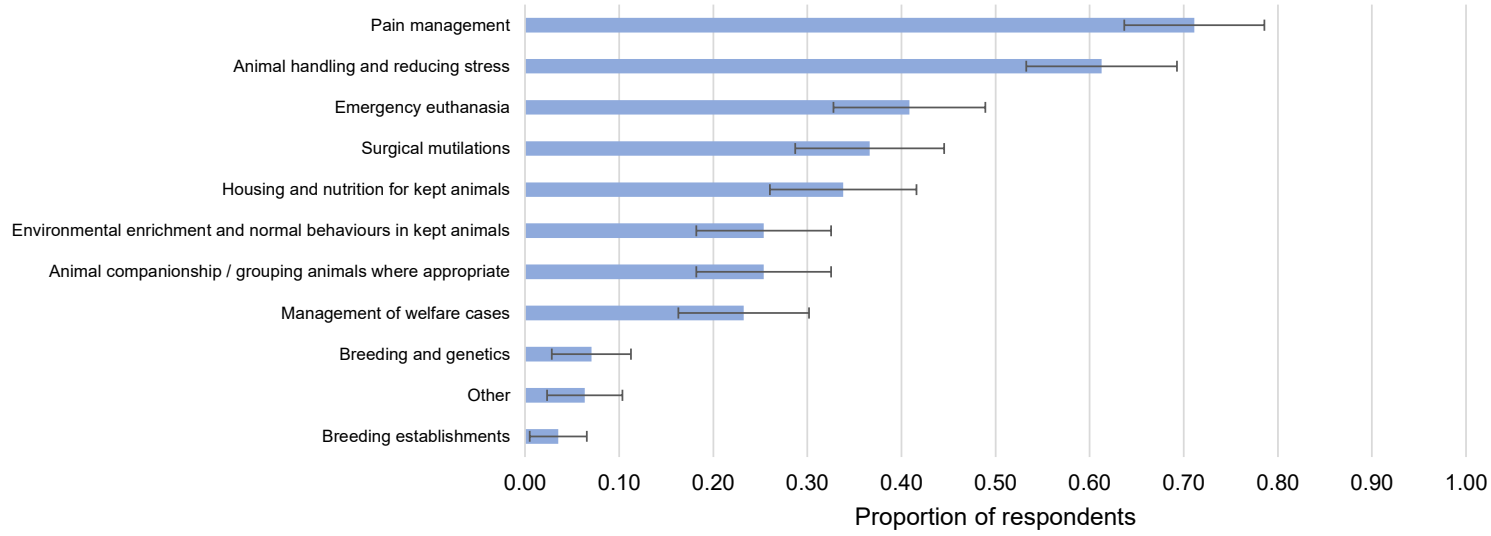

Figure 7: Issues covered by animal welfare guidelines in place at veterinary centres, as reported by survey respondents with 95% confidence intervals (n=142).

3.3.3 Promoting animal welfare

Of 313 respondents, 33% (102/313; 95% CI=0.27-0.38) reported to have an animal welfare policy at their practice, 38% (118/313; 95% CI=0.32-0.43) did not, and 30% (93/313; 95% CI=0.25-0.35) didn't know. Of those that did have a policy, 98 specified the elements it included (Figure 6). Respondents of practices *without* a policy were given the opportunity to specify any *guidelines* they had around animal welfare issues: see Figure 7. When asked what would support their practice in adopting an animal welfare policy, the highest percentage of 204 respondents (72%, 147/204; 95% CI=0.66-0.78) selected standards, guidance, and frameworks to follow. Animal welfare training topics suggested by 140 respondents were grouped into themes, and the three most popular were owner and public education on animal welfare and responsible animal adoption (21%, 29/140; 95% CI=0.14-0.27), breeding and reproduction including brachycephalic breeds (14%, 20/140; 95% CI=0.08-0.20), and environments for good welfare at home, in transport, at veterinary practices and in animal shelters (12%, 17/140; 95% CI=0.07-0.18).

3.3.4 Environmental impacts of animal husbandry

Respondents were asked if their practice occasionally, regularly, or routinely advised clients on environmentally responsible animal husbandry. Of 300 respondents, 31% responded 'yes' (92/300; 95% CI=0.25-0.36), 52% responded 'no' (157/300; 95% CI=0.47-0.58) and 17% didn't know (51/300; 95% CI=0.13-0.21). The majority of 87 respondents specified that this advice applied to cats and dogs (72%, 63/87; 95% CI=0.63-0.82), followed by exotic pets (39%, 34/87; 95% CI=0.29-0.49) and farmed livestock (29%, 25/87; 95% CI=0.19-0.38). Examples of topics for advice are shown in Table 7.

3.3.5 Promoting social wellbeing

Of 289 respondents, 40% had a policy on social wellbeing issues at their practice (117/289; 95% CI=0.35-0.46), 39% did not (114/289; 95% CI=0.34-0.45) and 20% didn't know (58/289; 95% CI=0.15-0.25). The most frequently included aspects are

displayed in Figure 8. When asked what would support their practice to adopt such a policy, the highest percentage of 172 respondents selected standards, guidance, and frameworks to follow (61%, 105/172; 95% CI=0.54-0.68).

3.3.6 Sustainability in the veterinary sector

A clear majority (71%, 159/225; 95% CI=0.65-0.77) favoured the production of educational materials and protocols for all staff as a means of supporting sustainability in veterinary workplaces (see Table 8). The majority of 255 respondents were interested in receiving training in environmental management in the clinic (76%, 194/255; 95% CI=0.71-0.81), the legal and regulatory sustainability landscape for veterinary practices (71%, 181/255; 95% CI=0.65-0.77), responsible medicine use to mitigate potential eco-toxicity (64%, 163/255; 95% CI=0.58-0.70), and environmentally responsible pet ownership (51%, 131/255; 95% CI=0.45-0.58). The most popular proposed intervention for supporting sustainability in the profession was the development of toolkits for practices, ranked as a first priority by 44% of 256 respondents (112/256; 95% CI=0.38-0.50).

Table 7: Examples of advice given to clients on environmentally responsible animal husbandry, by number and proportion of survey respondents with 95% confidence intervals (CIs) (n = 87).

Theme	Number	Proportion	(95% CIs)
Responsible use of parasiticides in small animals	18	0.21	(0.12 - 0.29)
Sustainable diets, feeding and packaging	11	0.13	(0.06 - 0.20)
Use of biodegradable poo bags and picking up dog waste	9	0.10	(0.04 - 0.17)
Biodegradable cat litter	8	0.09	(0.03 - 0.15)
Responsible use of parasiticides in farmed animals	7	0.08	(0.02 - 0.14)
Responsible use of parasiticides in equids	6	0.07	(0.02 - 0.12)
Responsible antibiotic use	6	0.07	(0.02 - 0.12)
Use of sustainable toys and enrichment materials for small animals and exotics	5	0.06	(0.01 - 0.11)
Advice on efficiency, productivity, and herd health planning in farm animal practice	5	0.06	(0.01 - 0.11)
Disposal of medicines and packaging	4	0.05	(0.00 - 0.09)
Grazing and soil management	4	0.05	(0.00 - 0.09)
Sustainable agriculture	4	0.05	(0.00 - 0.09)
Rescuing pets, neutering, and breeding advice	3	0.03	(0.00 - 0.07)
Risk of cats to wildlife / use of bells on collars	2	0.02	(0.00 - 0.05)
Manure disposal	2	0.02	(0.00 - 0.05)
Choice of pet	1	0.01	(0.00 - 0.03)
Preventative medicine	1	0.01	(0.00 - 0.03)
Biodiversity surveys on farms	1	0.01	(0.00 - 0.03)
Wildlife management and release	1	0.01	(0.00 - 0.03)
Avoiding use of chemical rodenticides	1	0.01	(0.00 - 0.03)

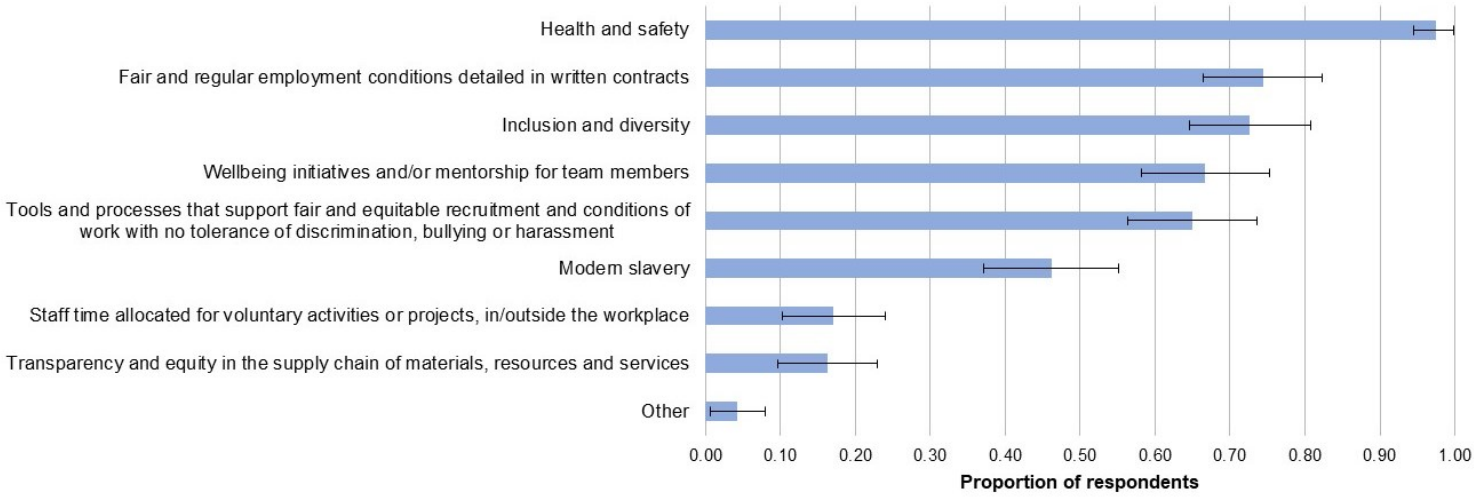

Figure 8: Elements included in veterinary practice social sustainability policies, according to survey respondents, with 95% confidence intervals (n = 117).

Table 8: Suggestions from survey respondents on the activities that they believe would help to drive sustainability in their veterinary workplaces, by number and proportion of survey respondents with 95% confidence intervals (CIs) (n = 225).

Theme	Number	Proportion	(95% CIs)
Education, training, resources, templates, guidance, signposting, protocols appealing to all staff	159	0.71	(0.65 - 0.77)
Accreditation, auditing, and benchmarking of veterinary practices	21	0.09	(0.06 - 0.13)
Campaign for regulation and policy change to veterinary institutions, drug companies, and government	20	0.09	(0.05 - 0.13)
Appeal to practice managers and corporate leaders to drive changes	13	0.06	(0.03 - 0.09)
Recommended supplier lists	11	0.05	(0.02 - 0.08)
Demonstrate the cost benefits of sustainable practices	9	0.04	(0.01 - 0.07)
Communications and marketing resources for veterinary practices	6	0.03	(0.01 - 0.05)
Research and provide more evidence where it is lacking	5	0.02	(0.00 - 0.04)
Practice and staff rewards systems including financial incentives	3	0.01	(0.00 - 0.03)
Case studies	2	0.01	(0.00 - 0.02)
Practice mentorship	1	0.00	(0.00 - 0.01)
Exercise group buying power / collective bargaining	1	0.00	(0.00 - 0.01)
Supply products; e.g., sustainable surgical kits	1	0.00	(0.00 - 0.01)

3.3.7 Solutions

In response to the results of the survey, a list of possible interventions to drive change under the previous five themes was compiled (Table 9), drawing from experience from other sectors in supporting sustainability outcomes. For each theme, approaches including voluntary initiatives, incentives (e.g., financial or technical support), command-and-control (i.e., mandatory regulations) and market-based instruments (i.e., policy instruments using markets and prices to incentivise organisations to reduce their impacts) are considered, for application at the level of teaching institutions, practice groups, membership associations and professional regulators.

Table 9: Potential programmes, incentives, and policy instruments for the veterinary professions to support ecological sustainability outcomes.

Veterinary role	Examples of ecological sustainability outcomes (Vet Sustain, 2020)	Examples of programmes and policy instruments to support outcomes
Managing the environmental impacts of veterinary services	Restoration of habitats and increasing biodiversity; Net zero; Use of 100% renewable energy; Clean air and water; Water recycling; Circular economy for packaging/ waste.	Undergraduate and professional education* Information and labelling (e.g., green accreditation schemes)* Grants or incentives (e.g., for green infrastructure; technology support)† Codes of practice‡ Emissions standards‡ Reporting requirements (e.g., carbon foot-printing)‡ Performance bonds (contracts based on meeting environmental obligations) §‡ Deposit-refund schemes for veterinary product packaging§
Responsible medicine use	Declining global AMR health burden; Declining environmental pollution with drug residues and resistance determinants.	Information and labelling (e.g., stewardship champions)* Grants or incentives (e.g., for diagnostic testing)† Codes of practice‡ Reporting requirements (e.g., for medicine sales and use)‡
Promoting animal welfare	A 'good life' for all species; A 'good 'life' for current and future generations.	Undergraduate and professional education* Information and labelling (e.g., supporting uptake of farm assurance schemes; welfare-friendly practice schemes)* Grants and incentives for practices (e.g., for welfare-centred modifications)† Grants and incentives for clients (e.g., for modifying farm production systems - supporting clients in the application process)† Codes of practice (e.g., alleviating stress in clinical settings; bans on cosmetic surgical mutilations)‡ Reporting requirements (e.g., on patient welfare outcomes)‡
Managing the environmental impacts of animal husbandry	Restoration of habitats and increasing biodiversity; Net zero; Use of 100% renewable energy; Clean air and water; Healthy soils; Water recycling; Circular economy for packaging/waste.	Undergraduate and professional education* Information and labelling (e.g., supporting uptake of farm assurance schemes)* Subsidies for clients (e.g., for environmental land management - supporting clients in the application process)§
Promoting social wellbeing	A 'good 'life' for current and future generations; Equality and diversity; Safe, fair, inclusive workplaces.	Information and labelling (e.g., good workplace and mentor schemes)* Grants or incentives (e.g., for wellbeing initiatives in practice or for collaborations with human health services on green or social prescriptions)† Codes of practice (e.g., for wellbeing initiatives in practice or to support vulnerable clients)‡

* Voluntary initiatives *(some of which are currently being implemented in the UK)*
† Incentives (e.g., financial or technical support)
‡ Command-and-control (i.e., mandatory regulations) *(some of which are currently being implemented in the UK)*
§ Market-based instruments (i.e., policy instruments that use markets and prices to incentivise organisations to reduce their impacts)

3.4 Discussion

3.4.1 Environmental impacts of veterinary services

Amongst the minority of respondents (17%, 68/392) who were aware of an environmental policy at their practice, waste policies were most frequently cited. A larger number of participants reported environmental actions (n=266) than the existence of policies (n=68), with waste recycling reported by a large majority (96%, 256/266). Non-waste-based interventions such as use of renewable energy were reported by a minority (13%, 35/266), indicating a primary focus on waste reduction and a narrow scope of environmental interventions at many veterinary centres. A desire was expressed by the majority for greater knowledge on sustainability solutions and guidance for practices to follow, a finding supported by other studies (Mair *et al.*, 2021).

Policy and practice to improve the environmental performance of the human healthcare sector and to address the health crises arising from healthcare pollution is considered an urgent imperative (Sherman *et al.*, 2020), with important insights to be extrapolated to the veterinary sector. Adoption of environmental policies may generate wider business benefits too: over half of 1,044 pet owners surveyed in the USA would pay more for veterinary services at a clinic with a reduced environmental impact, and would value sustainability certification to aid the identification of such practices (Deluty *et al.*, 2021). Other studies suggest that socially and environmentally responsible firms may hold a competitive advantage in attracting a quality workforce (Willness and Jones, 2013; Greening and Turban, 2016). Accreditations for a broad range of environmentally sustainable practises such as the RCVS PSS (RCVS, no date, b) and the IIE scheme (2019) should be leveraged, and other potential interventions outlined in Table 9 include grants and incentives to adopt green infrastructure, and emissions standards and reporting.

3.4.2 Responsible medicine use

The majority of respondents (72%, 243/339) reported an antibiotic use policy, aligning with the significant progress being made by UK veterinary professionals and their clients in antimicrobial stewardship (Singleton *et al.*, 2017; Wilson *et al.*, 2021; FAO and VMD, 2022). Although around half of the respondents reported to have a parasiticide policy at their practice, a minority included key recommendations of risk-based assessments and pre-treatment diagnostic testing as recommended by British veterinary associations (BVA, BSAVA and BVZS, 2021) in response to nascent ecotoxicity concerns about certain pet parasiticides. Many practices that did *not* have policies still implemented measures around medicine use and impacts, such as infection control and hygiene procedures, and parasiticide treatment protocols.

However, considering the gaps in policy and misalignment with recommendations from British veterinary associations at some veterinary centres, there may be inconsistencies in prescribing activities (as documented in other studies, e.g., Hughes *et al.*, 2013; Summers *et al.*, 2014). This may also present a risk of negative public health (Tang *et al.*, 2017) and ecosystem externalities, particularly relating to environmental drug residues (Perkins *et al.*, 2021; Wells and Collins, 2022). Potential interventions outlined in Table 9 include stewardship champions programmes and medicine use reporting requirements, the latter of which has been effective in other countries (Speksnijder *et al.*, 2015). Practises around the use of other medicines with potential ecosystem impacts such as non-steroidal anti-inflammatories (Cuthbert *et al.*, 2006; Herrero-Villar *et al.*, 2020), hormones (Bártíková *et al.*, 2016) and psychoactive drugs (Bean *et al.*, 2014) were not explored in this study.

3.4.3 Promoting animal welfare

A minority of respondents (33%, 102/313) reported having an animal welfare policy at their practice, but a larger number reported the use of animal welfare guidelines (n=142). Animal welfare training on owner and public education around responsible animal adoption/selection was suggested by the largest proportion of respondents (21%, 29/140), reflecting concerns for the problems arising from pet acquisition

reported by the People's Dispensary for Sick Animals (PDSA) in 2022 (PDSA, 2022). Codes of practice for clinical settings such as the use of animal handling and stress guidelines (as reported by 61%, 87/142) and clinical audits (Lloyd, 2017; Wensley *et al.*, 2020) can help veterinary centres to manage the unintended welfare impacts of veterinary consultations and treatment, and signal a welfare-centred approach (BVA, 2016). Other interventions included in Table 9 such as welfare outcome measure reporting requirements, and supporting farm animal clients with welfare grant applications could also address specific welfare issues in domestic settings in alignment with professional priorities (BVA, 2016; Rioja-Lang *et al.*, 2020).

3.4.4 Environmental impacts of animal husbandry

A minority of respondents (31%, 92/300) claimed that their practice occasionally, regularly, or routinely advised clients on environmentally responsible animal husbandry, with advice most commonly relating to cats and dogs, reflecting the respondent demographic. The provision of environmental advice represents a substantial, untapped opportunity for veterinary professionals to mitigate certain negative externalities and support the provision of public goods derived from domestic animals. Topics of sustainability relevance routinely discussed by veterinary professionals with clients include responsible breeding and neutering, obesity management, preventative health care, nutrition, and efficiencies in farmed animal production (Green *et al.*, 2011; Belshaw *et al.*, 2018). However, our results suggest that some are also extending their advice to important aspects such as appropriate dog faeces disposal (10%, 9/87) (De Frenne *et al.*, 2022) and minimising wildlife predation and disruption (2%, 2/87) (Holderness-Roddam, 2011; Loss *et al.*, 2013; Doherty *et al.*, 2016; Cecchetti *et al.*, 2021) in the companion animal sector, and grazing and soil management (5%, 4/87) and biodiversity surveys (1%, 1/87) in large animal practice (Llonch *et al.*, 2017; Maqbool *et al.*, 2017; Statham *et al.*, 2017). Further interventions outlined in Table 9 could include environmental education for veterinary professionals and assisting farm clients in the uptake of environmental subsidies and assurance schemes to support specific systems, such as agroecology (Tomlinson, 2020; Hayward, 2021).

3.4.5 Promoting social wellbeing

A 40% minority (117/289) of respondents stated their practice had a policy on the social aspects of sustainability, and “standards, guidance and frameworks to follow” were frequently desired. Mental health problems and workforce attrition (Platt *et al.*, 2012; Arbe Montoya *et al.*, 2021) persist as harmful social externalities of veterinary work, although guidance from the BVA (2020), mental health initiatives from RCVS and VetLife (Mind Matters, no date; VetLife, no date) and practice mentorship schemes are available to help address these issues. As included in Table 9, practices could consider establishing codes of practice to formalise the important personal and social support function of veterinary professionals as ‘community care givers’ and ‘trusted advisors’ (Devitt *et al.*, 2013; Lovatt, 2015), for example detailing their approaches to vulnerable clients and recognising and responding to signs of abuse (Boyden *et al.*, no date). Collaborations with the human healthcare sector on green and social prescriptions (Barton and Pretty, 2010) could further enhance the positive externalities of veterinary services.

3.4.6 Solutions

In a survey conducted by RCVS (2019), supported by others (Price, 2021), the veterinary profession was considered to be one of the most trusted in the UK, and similarly to other sectors, works within a ‘social licence to operate’. This refers to the implicit process by which communities approve an industry’s activities as socially acceptable, and grant it permission to conduct its business (Hampton *et al.*, 2020). Public concern regarding specific sustainability risks associated with veterinary work can erode this social licence and lead to government regulation (Hampton *et al.*, 2020).

However, industry self-regulation has been highly effective in many sectors (Sharma *et al.*, 2010; Leiringer, 2020; RUMA, 2020) in driving sustainability, helping to protect an industry’s social licence to operate. Voluntary initiatives to inform and certify veterinary service providers for sustainability credentials are gaining momentum, as evidenced by the 126 veterinary practices and organisations engaged in the IIE

accreditation scheme (April Soyomayor of IIE, personal communication, 8/12/22). However, survey respondents indicated that additional programmes to provide knowledge, standards, and guidance may support their practices' sustainability agenda. Sector-led solutions could therefore involve explicit inclusion of sustainability in the veterinary undergraduate curricula and postgraduate training, reinforced by performance standards, codes of practice, reporting requirements, and financial incentive schemes in practice, as used in other sectors to modify behaviours (see Table 9). Such initiatives could be implemented at the level of teaching institutions, practice groups, membership associations, and professional regulators.

Considering the multi-faceted role of veterinary professionals, this mix of incentives for positive externalities and abatement measures to mitigate negative impacts could help to reconcile the conflicts that are frequently navigated in veterinary practice, between the opposing private and public interest claims on valuable resources (Timmermann, 2021). For example, the responsibility to secure 'good life' opportunities for animals (FAWC, 2009) is sometimes in tension with maximising production in farmed animals (McInerney, 2004), and reducing antimicrobial and parasiticide use in pursuit of public health or environmental objectives may necessitate a change in current veterinary business models, whilst protecting against potential animal welfare trade-offs (Maes *et al.*, 2010; Reader, 2014; Statham, 2019).

3.5 Conclusions

Considering the earth's finite resources and the need to consider intergenerational and interspecies wellbeing, there is justification for the veterinary profession to build an ecological sustainability discourse that leverages its influence at the human-animal-environment interface. In addition to conceptualising sustainability for the veterinary context, opportunities for sustainability could be located at the level of veterinary centres and practitioners, and enacted through working policies and practises that accurately internalise (i.e., reward or penalise) the impacts of veterinary work.

Interpreted alongside previous studies, our results depict a value-action gap between the concern of veterinary professionals around sustainability issues, and the policies and practises they report at their workplaces. Wider adoption and implementation of policies and practises is required, supported by further information and guidance, in particular to mitigate the environmental externalities of veterinary services and the animals under veterinary care, and ensure safe, fair, and inclusive workplaces. Addressing the smaller gaps in policy identified in this survey could further alleviate animal welfare issues in clinical and domestic settings, and maintain momentum around responsible medicine use. Building on the progress made to date, additional sector-led programmes to address the policy, practice, and knowledge gaps could enhance veterinary contributions to the sustainability agenda and help to protect the sector's social licence to operate. Such programmes could involve a policy mix of education, reporting requirements, performance standards, and incentives, implemented at the level of practice groups, membership associations, educational institutions, and professional regulators.

3.5.1 Limitations

The authors recognise the limitations of using an iterative process to devise the research questions, rather than a standardised methodology, which would have been more robust. The participation of a self-selecting group of 392 individuals is a source of bias towards those interested in sustainability. The sample size of 392 was relatively low, considering over 5,000 practices are currently operating in the UK. The results reflect the responses of veterinary practice representatives in a variety of roles and their current awareness of policies and activities at their practices, which were not validated against any practice documentation. We acknowledge the possibility of discrepancies between the claims of survey respondents and the policies and activities of their practice or practice group. The term 'policy' was defined broadly as a written or generally agreed set of principles, which may have been interpreted differently between respondents, representing a source of inaccuracy in responses. Respondents were given the opportunity to declare *either* sustainability policies *or* activities at their practices; the translation of policy to practise was beyond the scope of this study.

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Authors' contribution statement

LEH, ZJH, JS, DHB and GR conceived the research and developed the survey. JS disseminated the survey and organised the responses for transmission to LEH for analysis. LEH performed the analysis, and wrote the manuscript with input from all authors. DM supported the economics framing of the research, LB supported the interpretation and presentation of results, and CO organised the ethical review and supervised delivery. All authors contributed to the final manuscript.

Ethics statement

Ethical approval for this study was granted by the RCVS Ethics Review Panel (Reference 2022-090-Oxtoby).

Funding and competing interests statement

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Data availability statement

The raw data collected in this study are not available because participants did not give written consent for their data to be shared publicly. However, tables of data relating to the five themes described are available from the corresponding author on reasonable request.

3.6 Next steps

This study highlights the crucial role, duty, and opportunity for veterinary professionals to support multiple facets of the sustainability agenda, including the neglected domains of animal welfare and antimicrobial stewardship (see Table 4). It documents the implementation of animal welfare and antimicrobial stewardship policies and practises by the majority of surveyed veterinary centres, suggesting that although these issues are subject to gaps in the wider UK public and private policy landscape, they remain key concerns for veterinary professionals and their clinical workplaces. Responding to research question 4, an array of interventions (Table 9) is proposed for further leveraging the roles of veterinary stakeholders to promote sustainability objectives. In particular, survey respondents repeatedly highlighted the need for more information and guidance to support their sustainability endeavours.

However, the results also suggest policy gaps amongst most of the surveyed veterinary centres around social wellbeing, environmental management in the clinic (beyond waste initiatives), and the environmental impacts of animals under veterinary care. These findings could help to inform approaches to the widely-documented mental health crisis within the UK veterinary profession (Mellanby, 2005). Mental health problems are also a sustainability issue (as defined by the Veterinary Sustainability Goals); but whether they *also* act as a *barrier* to advancing the other sustainability domains within veterinary workplaces, and/or emerge as an *outcome* of the tensions between public and private interests encountered in the animal-based industries, remains unclear. For example, it is possible that poor veterinary mental health may be linked to tensions between personal concern and professional obligations to animal welfare, and the deprioritisation of animal mental wellbeing within wider private and public policy, partly relating to private interests. These potential links warrant further research.

The environmental policy gaps observed in this study reflect the nascent environment movement within the veterinary sector, and the focus within the UK veterinary oath on ensuring the health and welfare of the animals *under veterinary care* – which presents risks of externalities impacting animals ‘beyond’ the clinic setting, i.e, wildlife, and ecosystems. For example, antibiotic stewardship is reportedly subject to

policies and practices at the majority of veterinary centres surveyed, and characterised by a trajectory of decreasing antibiotic use in UK farmed species, primarily driven by public health objectives (VMD, 2023b). However, the *ecological* impacts of antibiotics are of emerging concern (UNEP, 2023), following the course of parasiticides, which are currently subject to scrutiny, research, and policy responses from an ecological standpoint (BVA, BSAVA and BVZS, 2021; Perkins *et al.*, 2021). However, the synergies and tensions between the public health and ecological agendas for antibiotic use are yet to be identified.

The next chapter continues to explore the sustainability dimensions of veterinary care. In particular, it reconciles the significant progress in animal antibiotic stewardship for public health, with the potential environmental externalities of the antibiotics used in farmed species, to inform a One Health approach to responsible medicine use.

4. The environmental footprint of antibiotic use in UK terrestrial food-producing animals

Antibiotics are used in farmed species to support animal health and welfare. However, antibiotic residues and resistance genes have been detected in the vicinity of human activity, including farm settings, with growing concerns regarding their impact on ecosystems. This chapter responds to research question 2, to understand the role of veterinary professionals in supporting antimicrobial stewardship but in the context of the broader sustainability agenda. It critically reviews the impacts of farm AMU on the environment, including non-target organisms. Existing data on the antibiotic classes in use in UK terrestrial farmed animals, their public health categorisations, and their potential environmental impacts are collated into a novel One Health risk matrix. This tool aims to support medicine stewardship by prescribers, animal keepers, and regulators in pursuit of human, animal, and environmental health outcomes.

4.1 Introduction

Antibiotic resistance is amongst the most significant and pressing health challenges facing human civilisation. It was directly responsible for an estimated 1.27 million human deaths and indirectly associated with a further 3.6 million worldwide in 2019 (Murray *et al.*, 2022) – impacts that reflect a decline in the efficacy of the antimicrobial compounds that have defined and supported medical progress since their widespread adoption (Kirchhelle, 2018).

Although public health outcomes are the focus of the global antibiotic stewardship agenda (FAO *et al.*, 2022b), the potential *environmental* impact of AMU is also an area of growing concern. Arising from both human and animal healthcare applications, antibiotics have been detected in a variety of environmental compartments, such as ground and surface waters, soils, and the air (Yang *et al.*, 2021; Rossi *et al.*, 2023). Ecological consequences of antibiotic residues in these

settings have been documented, including toxicity toward non-target organisms (Yang *et al.*, 2021) and the emergence of resistance determinants that can hamper natural microbial community structure and functioning (Grenni *et al.*, 2018). Considering the mounting biodiversity crisis, characterised by a rapid decline in most indicators of ecosystems and biodiversity (IPBES, 2019), opportunities to mitigate the ecological risks of antibiotic use are being explored in a variety of disciplines (Duane *et al.*, 2019; EC, 2020; Cussans *et al.*, 2021), including in the animal health sectors (BEVA, 2021; BSAVA, 2022).

Although the presence and ecological repercussions of antibiotic residues and resistance determinants have been linked to animal agriculture (Kumar *et al.*, 2005; Sarmah *et al.*, 2006), the environmental impacts have not been summarised for stakeholders within the UK farming sectors. Recent progress in antibiotic stewardship in UK agriculture as a public health imperative (VMD, 2023b) has, to date, not been informed by or reconciled with the environmental impacts of antibiotic classes, to identify the co-benefits and trade-offs between One Health objectives.

This critical review aims fill this gap, primarily asking “what are the environmental impacts of antibiotic use in UK terrestrial farmed animals?” The review is structured around two aims: (1.) Firstly, to synthesise the existing scientific evidence of the environmental impacts of AMU in UK terrestrial farmed animals, it traces the route, fate, and impacts of antibiotics and resistance determinants from manufacture to environmental discharge, critically identifying knowledge gaps at each stage; (2.) Secondly, to depict the environmental footprint of the antibiotic classes in common use in UK farmed animals and inform antimicrobial stewardship with One Health objectives, a risk matrix is constructed, combining antibiotic usage, excretion, and persistence data, with public health risk categories and ecological impact thresholds. A discussion and conclusions are then presented.

4.2 Methods

To address the research questions, a critical narrative review was conducted, based on a modified version of the Quick Scoping Review method (Collins *et al.*, 2015). This involved: (1.) clearly defining the aims (as described in section 4.1); (2.) creating a schematic diagram, in this case to identify steps in the pathways of antibiotic residues and AMR determinants from source to the environment; (3.) conducting a non-systematic literature search of peer-review publications and grey literature to describe these pathways; this review also involved the collation and synthesis of data from the literature on current levels of antibiotic usage in UK farmed animals, and excretion profiles, half-lives[16] in environmental compartments, and ecological impact thresholds of each antibiotic class in use; (4.) compiling and presenting the final databases and risk matrix; and (6.) identifying evidence gaps and future research needs. This review was undertaken between July and September 2023, and finalised in February 2024.

On encountering a fragmented and incomplete research base for this topic, particularly in relation to excretion profiles and half-lives of veterinary antibiotics, a narrative scoping review (Munn *et al.*, 2018; Sukhera, 2022) utilising peer-reviewed literature as well as regulator product impact summaries was considered most appropriate for creating a complete database of risk factors for each antibiotic class. The review involved a PubMed database search using the terms “environmental impact” OR “ecological impact”, AND “antibiotics” OR “antimicrobials” OR specific antibiotic class and agent names, AND key search terms identified in Figure 9 relating to steps in the pathway. The snowball method (Wohlin *et al.*, 2022) was also used to identify further references related to the research questions and to expand the database of risk factors, until a minimum of one datapoint was cited for each risk factor for every antibiotic class in use. Papers and references from the past 80 years were included.

In this review, the scope of medicines is constrained to antibiotics, defined as naturally occurring, semi-synthetic, or synthetic substances that kill or inhibit the

[16] Half-life is the time period required for the substance to reduce by half of its initial quantity.

growth of bacteria (Andreoletti *et al.*, 2008). Antibiotic use in terrestrial farmed species in the UK context are the focus; however, where relevant, research and experiences from different countries, regions, and sectors are included. Human antibiotic use was included in the review alongside the farmed animal context, in recognition of their shared antibiotic classes and the inextricable links between their pathways to the environment. Furthermore, environmental impacts of the *processes* of manufacturing and distributing antibiotics destined for farmed animal use are excluded from our scope.

4.3 Results

4.3.1 Steps in the antibiotic residue/AMR pathway

The potential sources and steps in the pathways of antibiotics and AMR determinants are mapped in Figure 9. Antibiotics include both their parent compounds and their metabolites; resistance determinants comprise both resistant bacteria and antibiotic resistance genes (ARGs). Each step in the pathway of antibiotic residues and AMR determinants from their natural and anthropogenic sources, to their eventual discharge into the environment, is described in the following sections.

4.3.2 Natural sources of antibiotics and resistance determinants

Antibiotics occur ubiquitously in the natural environment, produced by microorganisms competing for resources within a shared environmental niche. Indeed, more than three-quarters of the antibiotic compounds used in medicine today are natural products, with most derived from the secretions of *Streptomyces* bacteria isolated from soil samples (Kieser *et al.*, 2000; Durand *et al.*, 2019). However, naturally-occurring antibiotic compounds are thought to exert their effect on a micro-scale, with concentrations presumed to drop rapidly around their source, limiting their exposure and impact on the wider ecological community (Larsson, 2014a; Larsson and Flach, 2021).

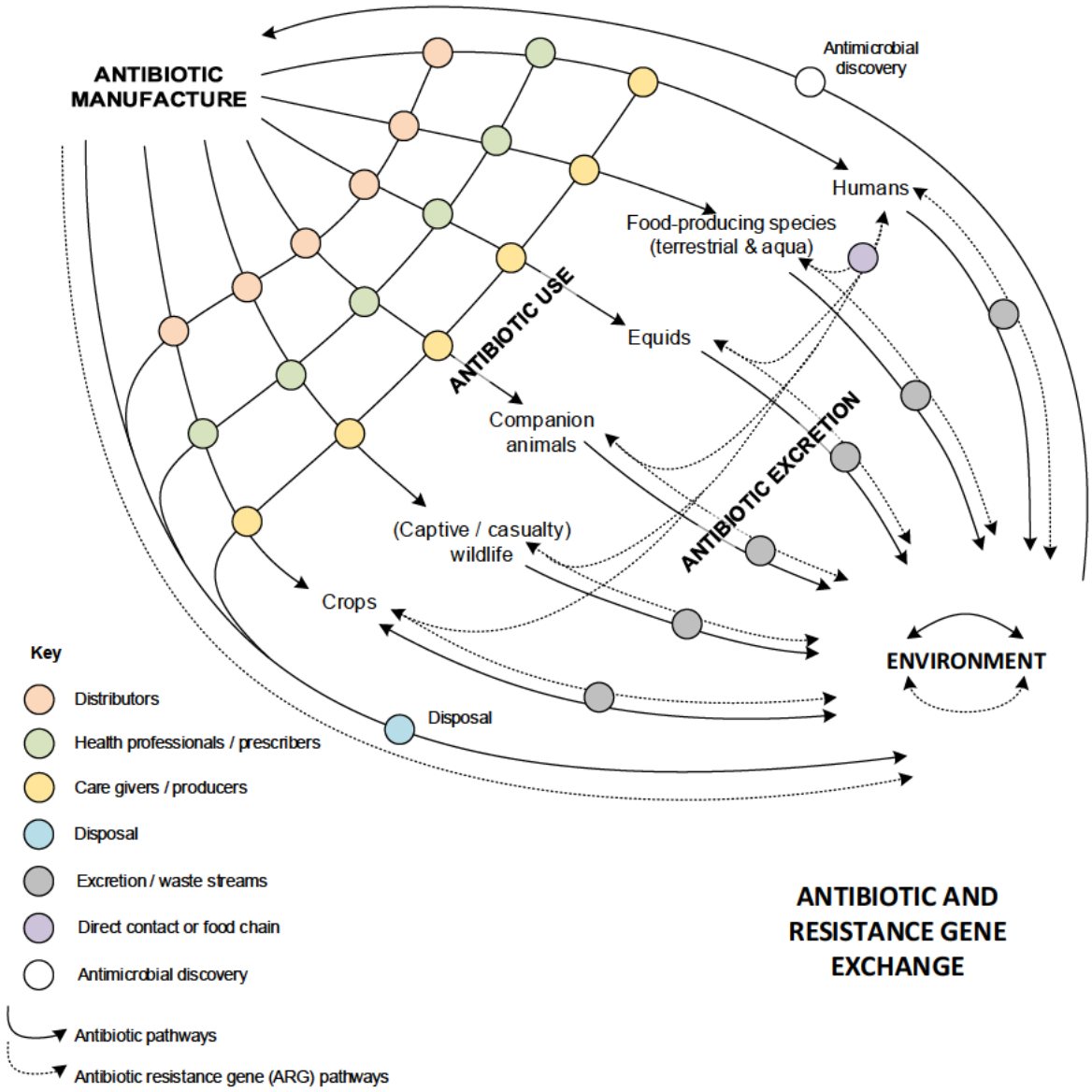

Figure 9: Schematic illustration of the potential flows of antibiotics and antibiotic resistance genes between their sources (antibiotic manufacture/production, and natural sources), and the environment. The diagram includes several 'nodes' within the pathway, also representing intervention points, including antibiotic distribution, prescription/supply and administration, drug disposal, excretion and waste streams, the food chain, direct contact with animals/plants, and antibiotic discovery.

Antibiotic resistance determinants also have ancient natural origins and have been discovered in pristine environments untouched by human influences, such as isolated caves and permafrost cores (Olivares *et al.*, 2013; Larsson and Flach, 2021). These entities continuously circulate amongst bacteria and environmental compartments (i.e., air, water, sediment, and biota), forming a so-called 'intrinsic resistome'[17] of genetic sequences that are naturally exchanged between bacteria, offering novel survival strategies and competitive advantage including mechanisms of AMR (Marti *et al.*, 2014). All antibiotic classes approved for human and veterinary medicine have been met by resistance amongst some of the pathogens they target, suggesting that external environments already harbour resistance factors for all antibiotics that will ever be developed (Larsson and Flach, 2021).

4.3.3 Human sources of antibiotics and resistance determinants

Human activities have become an increasingly significant source of antibiotics and resistance genes in the environment. Naturally-occurring antibiotics have been extracted and utilised by humans for centuries, with early records documenting the use of copper salts and filamentous fungi growing on bread in the treatment of wounds and burns in ancient Egypt (Pećanac *et al.*, 2013). However, during the 19th century, scientists began to observe the inhibitory effects of various moulds and bacteria on infections, and by the early 1900s, derivatives of natural antibiotics began to be commercialised. Arsphenamine was marketed for use against syphilis in 1911; sulphanilamide was commercialised in 1935 and used by soldiers during World War II; and penicillin, accidentally discovered by Alexander Fleming in 1928, was brought to market in 1945 (Royal Society of Chemistry, 1999; Durand *et al.*, 2019).

These discoveries paved the way for the 'golden age' of antibiotic discovery between the 1940s and 1970s, during which all current antibiotics - more than 20 classes - were unearthed from dozens of bacterial species and fungi (Durand *et al.*, 2019), transforming human and animal healthcare. They were also applied to farmed animal agriculture, aquaculture, and horticulture from the 1930s, to control disease, increase feed conversion efficiencies, promote growth, and preserve food (Kirchhelle, 2018).

[17] The 'resistome' is the reservoir of resistance determinants that can be mobilised into the microbial community (D'Costa *et al.*, 2006).

Although the use of antibiotics is now widespread on farms globally, AMU practices in animal and human settings have evolved significantly in response to public health concerns regarding the 'silent pandemic' of AMR. For example, usage on a per-animal basis has declined globally in recent years, evidenced by data representing 65% of the global animal biomass suggesting an overall decrease of 13% in reported antibiotic use in mg/kg between 2017 and 2019 (from 111.45 mg/kg to 96.73 mg/kg) (WOAH, 2022a). A 21% reduction in antibiotic sales for food-producing animals in 31 European countries over the same period has been reported (European Medicines Agency (EMA), 2019, 2021), and in the UK, sales of veterinary antibiotics for use in farmed species decreased by 59% (from 62.3 to 25.7 mg/kg) between 2014 and 2022 (VMD, 2023b). Stewardship efforts in the UK human health sector have also resulted in an 18% reduction in antibiotic use in people (from 125 mg/kg to 103 mg/kg, excluding private prescriptions) between 2014 and 2019 (VMD, 2023a).

Notwithstanding this important progress, a total of 706 tonnes of antibiotic active ingredients were dispensed in 2019 in the UK for use in people (68% of total) and animals (32%) (VMD, 2023a), reflecting human activity as the most significant source of antibiotics in the natural environment (Larsson and Flach, 2021). In turn, the resistome is altered and augmented by anthropocentric activities that release antibiotics, disinfectants, heavy metals, and resistance genes into the environment (Marti *et al.*, 2014). The pathway of anthropogenic antibiotics and AMR determinants begins with pharmaceutical manufacturing.

4.3.4 Manufacture of antibiotics

Antibiotics can enter the environment in the process of producing active ingredients or during their formulation at pharmaceutical manufacturing sites (Larsson, 2014a). A number of studies have highlighted the discharge of antimicrobial substances from such facilities across the world, including in Korea (Sim *et al.*, 2011), Taiwan (Lin *et al.*, 2008), Canada (Kleywegt *et al.*, 2019), Switzerland (Ortelli *et al.*, 2009), Croatia (Bielen *et al.*, 2017), Denmark (Holm *et al.*, 1995), and in the major production areas of India and China that serve the global bulk drug market and produce half of the world's active pharmaceutical ingredients (Fick *et al.*, 2009; Kleywegt *et al.*, 2019).

Most of these studies detected antibiotics in wastewater arising from manufacturing facilities; however, authors of the Denmark study found antibiotic substances (sulphonamides) in leachate plume from a landfill site, in which pharmaceutical production waste was disposed (Holm *et al.*, 1995).

The total quantities of antibiotics released from manufacturing facilities is generally small compared to those attributed to patient excretion, and in some cases the detected levels appear to attenuate with distance from their point source due to dilution, sorption, and degradation (Holm *et al.*, 1995). However, the local environmental concentrations of pharmaceuticals arising from manufacturing facilities can be much higher than those resulting from patient usage (Bielen *et al.*, 2017; Vestel *et al.*, 2022). For example, one study of a major drug production area in India detected antibiotics in recipient drinking water within nearby village wells, including ciprofloxacin at concentrations exceeding 1µg/L, which is likely to select for resistance (Fick *et al.*, 2009; Bengtsson-Palme and Larsson, 2016).

To better understand the levels of antibiotic discharge from such sources and their impact on local ecosystems, researchers have assigned Predicted No-Effect Concentration (PNEC) values to different antibiotic substances. In addition, the AMR Industry Alliance (AMRIA), consisting of pharmaceutical and biotechnology companies, has created an 'Antibiotic Manufacturing Standard' and roadmap, adopted by several pharmaceutical companies at the UN High-Level Meeting on AMR in 2016 (AMRIA, 2018). A 2023 progress report from AMRIA indicated that most products (88%) manufactured at Alliance members' sites have been assessed against PNEC targets (AMRIA, 2023a), and most of the assessed products (84%) meet these targets (AMRIA, 2023b). However, the proportion of antibiotics utilised in the UK medical and veterinary sectors that are manufactured at third party facilities, and the environmental footprint associated with these production plants, remains unknown.

As well as antibiotic residues, industrial effluents may also contain AMR bacteria and genes, including mobile genetic elements (Šimatović and Udiković-Kolić, 2020). Studies based on sampling and analysis of pharmaceutical wastewaters for resistance determinants have taken place in China, India, Tunisia, and Croatia.

These studies estimated that around 10^{12}–10^{14} ARG copies could be released per day from the pharmaceutical wastewater treatment plants sampled in China (Guo *et al.*, 2018), and 104 colony forming units/100 ml were isolated in wastewater from a ß-lactam and quinolone production unit in Tunisia (Tahrani *et al.*, 2017). Although this evidence does not cover all countries including the UK, it indicates that some wastewater treatment processes are not 100% effective in removing resistant bacteria or resistant genes, presenting a risk of local AMR development downstream from pharmaceutical plants from which antibiotic residues are discharged (Tell *et al.*, 2019). A clearer understanding of the risks of AMR discharge from UK-based antibiotic manufacturing facilities, *and* third-party antibiotic production sites supplying UK animal agriculture, is required.

4.3.5 Disposal of unused antibiotics

Disposal of unused antibiotics can occur along the antibiotic value chain, from manufacture to end user. Discarded medicines may include expired, unused, surplus, and contaminated pharmaceuticals, and are defined in the UK as clinical waste, controlled by waste regulations that instruct their disposal in landfill sites designed to accommodate hazardous waste or via incineration (Bound and Voulvoulis, 2005). These practices are supported by good practice guidelines for the devolved regions of the UK and within the RCVS Practice Standards Scheme (RCVS, no date, b; BVA, 2011).

Once dispensed to or purchased by a member of the public (e.g., a patient or animal keeper), any unwanted pharmaceutical products are classified as household waste, and their disposal is not subject to controls in the UK (Bound and Voulvoulis, 2005). Manufacturer packaging usually recommends disposal by returning the product to the pharmacist, and most European countries have a return scheme for unused and expired pharmaceuticals. However, studies have shown that returning drugs to pharmacies is only practiced largely in Germany and Sweden (Paut Kusturica *et al.*, 2017), and disposal via the sink or toilet or in normal household waste is common in many countries (Bound and Voulvoulis, 2005; Paut Kusturica *et al.*, 2017). Other studies have shown that up to 43% of people surveyed in Germany (Goetz and Keil,

2007), 35% in USA (Glassmeyer *et al.*, 2009), and 12% in the UK (Bound and Voulvoulis, 2005) dispose of medicines at least occasionally down the sink or toilet. One review cited household waste as the main route of disposal for unwanted medicines in the UK (Paut Kusturica *et al.*, 2017), and subsequent leakage from household landfill sites would risk groundwater contamination.

Little evidence is available regarding the most common practices around the disposal of expired, contaminated, or surplus drugs amongst UK farmers. Most veterinary practices offer take-back schemes for medicines (RUMA Companion Animal and Equine (RUMA CA&E), 2023), but the uptake of this service is unknown. Antibiotic Amnesties were held in 2022 and 2023 by NHS England and Scotland and veterinary stakeholders to encourage pet owners to return any of their pets' leftover antibiotics to veterinary practices for safe disposal (Allerton *et al.*, 2022), although this did not include the farming sector.

The formulations, methods of packaging, and pack sizes vary between human and animal antibiotics, and are likely to affect the selected routes of disposal. For example, the tablets associated with human antibiotic preparations would be more readily discarded down wastewater channels than the multi-use glass vials, boluses, and medicated feedstuffs that may be found in farmed animal settings. However, there may also be specific exceptions relating to liquid formulations – one review from 2006 stated that most farmers who use antibiotic footbaths dispose of waste antibiotics in slurry, which was assumed to result in their inactivation (Laven and Logue, 2006). More research in to disposal practices is required for this antibiotic pathway to be fully characterised.

4.3.6 Emergence and transmission of resistance determinants

Following the purchase and consumption of antibiotics by human or animal patients, there is an increased risk of resistance emergence, which can subsequently reach the natural environment. A meta-analysis by Bell *et al.* (2014) found that increased antibiotics use by people produced greater resistance at the individual patient level but also at community, country, and regional levels. Amongst many studies in the

farmed animal sectors, authors of two national-level studies found that the usage of specific antimicrobials strongly correlated with the level of resistance in commensal *E. coli* isolates in pigs, poultry, and cattle (Asai *et al.*, 2005; Chantziaras *et al.*, 2014). Although the relationship between animal AMU and the emergence of AMR is multifactorial and dependent on the antibiotic-bacteria combination, antibiotic use increases the probability that AMR will arise (Parascandola and Weed, 2001).

Antibiotic resistant bacteria emerging in human and animal patients can be excreted via several routes, including in urine, faeces, respiratory and skin secretions, and - in the case of farmed species - animal-source foods (Food Standards Agency (FSA), 2022). The shedding of AMR bacteria can present a risk of infection to other humans and animals, with compelling evidence of transmission both within and between human and animal populations (ECDC *et al.*, 2017; Koutsoumanis *et al.*, 2022; Redman-White *et al.*, 2023; UK Health Security Agency, 2023; WHO, 2011). This effectively amplifies the load and distribution of resistance determinants that subsequently enter the environment. Researchers have documented reverse zoonoses (humanosis) including gene-spillover of human-derived tetracycline resistance from people to bovines, canines, seals, and fish (Richards *et al.*, 2019), and cephalosporin resistance from human settings to wildlife (Palmeira *et al.*, 2021), illustrating the potential for AMR arising from human activity to impact wildlife populations.

Within the crop sector, herbicides and insecticides can catalyse AMR by raising the Minimum Inhibitory Concentration (MIC) for certain antibiotics, thus allowing them to more readily induce AMR evolution (Haynes *et al.*, 2020). For example, when *E. coli* and *Salmonella Typhimurium* were exposed to low levels of herbicides (including glyphosate, dicamba, and organo-modified polydimethyl siloxans-based products), they were able to tolerate ciprofloxacin above its normal MIC (Kurenbach *et al.*, 2018), enabling ciprofloxacin-resistant mutants to arise and persist. Heavy metals, pesticides, herbicides, and polychlorinated biphenyls (PCBs) are amongst several emerging pollutants that may enhance the negative impacts of antibiotics and AMR on the environment. Similarly, microplastics can adsorb antimicrobials onto their surface, amounting to a combination with cumulative toxic impacts on aquatic organisms and ecosystems (Pagaling *et al.*, 2023; Wang *et al.*, 2023).

4.3.7 Excretion of antibiotics and resistance determinants

Current evidence indicates that human and animal excretion is the primary route of antibiotic discharge into the environment (Larsson and Flach, 2021). Once consumed by the end user, antibiotics are absorbed and metabolised, and 8-100% of the dose (depending on the class) is excreted in the faeces and urine as the active parent compound (Polianciuc *et al.*, 2020). Following human antibiotic consumption and excretion in private households and hospitals, pharmaceuticals primarily enter the environment via municipal wastewater (Polianciuc *et al.*, 2020; Healthcare Without Harm, 2021). One study detected antibiotics at concentrations of 68.7 µg/L in non-UK hospital effluent samples (Omuferen, Maseko and Olowoyo, 2022).

Similarly, following the treatment of farmed animals, veterinary antibiotics principally enter the environment via the discharge of manure onto land (Gothwal and Shashidhar, 2015; Umwelt Bundesamt, 2018; Yang *et al.*, 2021). Depending on the species and husbandry system, manure is either deposited onto land directly, or it is collected or washed down farm drainage channels and stored in slurry stores or manure heaps. Many studies have documented the presence of antibiotic compounds within animal faeces across the world, including a literature review of studies collectively analysing 1,568 manure samples from Asia, the Americas, and Europe. Sulphonamides were detected in pig, cattle, and poultry manure at concentrations between 0.002mg/kg and 235mg/kg (in pig manure in Japan and Germany, respectively) (Wohde *et al.*, 2016). Levels of tetracyclines in slurry from the same species varied from 0.005mg/kg to 764mg/kg (in pig manure in Japan and China, respectively) (Wohde *et al.*, 2016). Considering the EMA guideline maximum threshold of 0.1mg/kg for residues of veterinary pharmaceuticals in soils (EMA, 2008), these data are indicative of high levels of local variation, but significant environmental concentrations of antibiotics in manure in some agricultural settings.

Comparing animal production systems, the transfer of excreta is immediate and direct on a seasonal or year-round basis in extensively managed grass-based systems. For indoor production systems and stages, manure and slurry are collected, with field heaps and slurry lagoons being common methods of storage. System comparisons should consider potential differences in AMU levels between extensive

(e.g., outdoor; pasture-based; organic) and intensive (i.e., indoor; intensive) production systems, and the implications of these production practices on the magnitude and distribution of antibiotics on ecosystems.

The evidence regarding predictors of antibiotic use in farmed animals is fragmented, with significant research gaps in the associations between usage and particular farming systems and species. However, a recent review highlighted that organic production typically shows significantly lower AMU than other systems such as indoor, across a range of terrestrial farmed species, namely dairy and beef cattle, pigs, and broiler chickens (Redman-White *et al.*, 2023). Although a number of other studies also correlate outdoor and extensive production systems with lower average AMU than indoor intensive production (Stevens *et al.*, 2007; Moser *et al.*, 2020; Nielsen *et al.*, 2021; Matheson, Edwards and Kyriazakis, 2022), associations between production system and antibiotic use are complex and multi-factorial in nature, with assurance scheme restrictions, regulatory requirements, biosecurity, herd health planning, and social and behavioural factors representing important influences (da Costa and Diana, 2022; Redman-White *et al.*, 2023). Furthermore, there are challenges in categorising production systems for research purposes; for example, although organic certification is a useful binary differentiator, not all outdoor/extensive systems are organic certified. Further research in this area is warranted to explore the specific production system *characteristics* associated with antibiotic use.

There is also a paucity of evidence relating to the comparative magnitude and distribution of antibiotic effluent between farmed animal production systems. Given the typically lower levels of AMU in organic systems and some outdoor systems, it follows that total antibiotic discharges may be generally lower in outdoor than indoor systems. However, when antibiotics are used in outdoor settings, the diffuse distribution of untreated manure directly to soils across a land area may represent a pathway to water courses with few opportunities to attenuate the concentration of residues. Indoor production systems often involve the collection and storage of manure and slurry in specific and strategically-placed locations on farm, representing a point source of local discharge, but potentially limiting diffuse contamination of water courses, and waste can be stored and treated prior to spreading to promote

the degradation of contaminants. These generalisations merit further research to elucidate the magnitude and distribution of antibiotic discharge from farmed animals on a per-animal (or per unit product) and per land area basis, in different production systems.

Considering evidence of the presence of antibiotics in hospital wastewater, questions arise regarding the antimicrobial load in veterinary practice effluent. Farmed animal patients may occasionally be accommodated in veterinary practices or veterinary hospitals, as well as companion animals and equine patients, with a potentially significant proportion receiving antimicrobial treatments. Urine and faeces from farmed animals and equids may be removed and managed in a similar way as in farmed animal settings, and small animal faeces disposed of using bags in landfill. Although there is a possibility of some faeces and urine entering wastewater systems via the washing of bedding *etc*, there is a knowledge gap with limited to no evidence in the published literature about antibiotic loads within veterinary practice or veterinary hospital effluent.

Turning to resistance determinants, it is likely that AMR determinants primarily enter the environment via human and animal urine and faeces, considering their high volumes and pathways to the environment via wastewater facilities, manure/slurry storage facilities, or direct land application. Researchers have shown that hospital wastewater reflects inpatient activity in human hospitals (Perry *et al.*, 2019), concluding that length of stay and AMR gene abundance are positively correlated. Another study from the Netherlands found that hospital wastewater contained approximately 25% more antibiotics and up to 1.8-fold higher resistance gene concentrations than communal wastewater (Paulus *et al.*, 2019). In the animal sector, one study of a dairy farm in Nottinghamshire concluded that animal slurry stores can reflect the AMR status of the whole farm, including its current and previous AMU as well as the broader environmental and human input into the farm microbiome (Baker *et al.*, 2022). Indeed, resistance determinants are commonly isolated from animal waste: a global review found that cattle, chicken, and pig manure and sewage sludge were the primary sources of AMR genes in agricultural soils, and sulphonamides, tetracyclines, fluoroquinolones, and their corresponding resistance genes were the main types identified (Wu *et al.*, 2023).

4.3.8 Antibiotic residues in animal products

There is a theoretical pathway for antibiotics consumed and metabolised by farmed animals to enter the environment via animal-source foods. Strict withdrawal periods are established to prevent antibiotic concentrations in foods that transgress European maximum residue limits (MRLs). Routine surveillance conducted by the FSA suggests that the incidence of non-compliance with withdrawal periods is relatively low in the UK (UK Government, 2023b), compared to countries in which food contamination represents a serious public health issue (Treiber and Beranek-Knauer, 2021). Considering withdrawal period compliance and the ameliorating effect of storage, cooking, and human metabolism on antibiotic concentrations, food residues as a potential route for antibiotics to enter the environment is likely to be negligible in the UK.

4.3.9 Treatment and disposal of waste

Following excretion, human waste is usually collected and processed in wastewater treatment plants and incinerators, and animal waste from indoor production usually enters manure heaps and slurry lagoons. The treatment of human wastewater in the UK generally involves the ‘Activated Sludge Process’, which remains the most widespread wastewater treatment technology for the removal of key pollutants from municipal wastewater (Uluseker *et al.*, 2021). Antibiotics are primarily removed from water during sludge segregation, and after secondary wastewater treatment, the reduction in soluble antibiotics in water can reach 100% for sulphamethazines, sulphamethoxazole, tetracycline, ciprofloxacin, erythromycin, and trimethoprim (Karthikeyan and Meyer, 2006; Chilian *et al.*, 2022). However, certain antibiotics appear to have poorer removal rates; for example, macrolides have been detected in post-treatment water effluent at concentrations higher than their estimated PNEC, at 45 UK wastewater treatment plants on 20 occasions (Comber *et al.*, 2018).

Human wastewater is sometimes used for agricultural spray irrigation. However, due to the limited ability of waste treatment processes to remove pharmaceuticals, and the lack of regulation in the UK or Europe specifically aimed at curtailing antibiotics in

wastewater, antibiotics excreted by people can reach agricultural land. Hayes *et al.* (2022) concluded that a high resistance selection risk is posed by ciprofloxacin (a human antibiotic as well as the metabolite of enrofloxacin) in wastewater influent and effluent in the UK (Hayes *et al.*, 2022). In addition to environmental impacts, this presents a potential risk of crop contamination with antibiotics, and a research gap has been identified around the consequences of this practice on food crop quality and human health (Malakar *et al.*, 2019).

The settled solids produced during human wastewater treatment are used for energy or in construction, disposed of via incineration and landfill, or applied to land as agricultural fertiliser (Kinney *et al.*, 2006; Jaffrézic *et al.*, 2017). The latter is regulated in the UK and in Europe and represents the destination of 53% of wastewater sludge amongst members of the EU-15, which included the UK (Wu *et al.*, 2023). This practice helps to reduce reliance on inorganic inputs and achieve nutrient circularity. However, antibiotics have often been found in human sludge at concentrations ranging from a few nanograms to 100 mg/kg dry matter (Larsson, 2014a; Ezzariai *et al.*, 2018), representing a route of entry into the environment via organic fertiliser. Surplus sludge is incinerated to 550^{o}C to reduce its volume for disposal via landfill sites, or to transform it into useful products for the construction industry (Reijnders, 2018). It is understood that non-incineration methods of treatment are ineffective in removing many pharmaceutical products; however, antibiotics are believed to completely degrade during incineration, together with antibiotic-resistant bacteria, intestinal parasites, and various chemical compounds. The generation of furans, dioxins, and heavy metals in sludge ash, however, appear to present environmental and public health concerns (Vivek *et al.*, 2019; Chilian *et al.*, 2022).

The application of animal manure to farmland is also a common and regulated practice in the UK (UK Government, 2022; Boxall *et al.*, 2009), again supporting a circular nutrient economy and reduced synthetic fertiliser use. However, slurry and manure can contain antibiotic residues (Kim *et al.*, 2012; Prosser and Sibley, 2015), and various studies indicate their role in environmental contamination: a meta-analysis revealed that the proposed EU threshold for maximal environmental contamination by veterinary antibiotics in soil (0.1mg/kg EMA (2008)) has been

exceeded in many countries including the UK, in which sulphonamides were detected at concentrations of 0.3 ± 0.01 mg/kg (Frey *et al.*, 2022).

Manure and slurry storage can foster the degradation of contaminants to varying extents. Indeed, sulphonamides, beta-lactams, macrolides, and aminoglycosides can be significantly degraded during typical manure/slurry storage regimes, but quinolones and tetracyclines are likely to persist (Boxall *et al.*, 2002). One study found that veterinary pharmaceutical concentrations during a storage period of six months could decrease between 10 and 98%, depending on the compound (Kim *et al.*, 2012). Other treatments such as composting, fermentation, and anaerobic digestion can be applied to improve sludge/manure quality, remove residues, and derive additional sources of energy and revenue, with varying impacts on antibiotics present.

Composting, a well-known process involving the self-heating of aerobic manure to decompose organic matter, can reduce the concentration of certain antibiotics by 17-100% (Ezzariai *et al.*, 2018). Removal rates by composting appear to vary according to a combination of factors such as temperature, microbial community (i.e., the type of animal manure involved), the presence of substrates for adsorption, and the antibiotic compound. One study found that tetracycline and sulphonamide removal was highly dependent on the presence of sawdust, but tylosin removal was not (Kim *et al.*, 2012). Elimination rates of over 90% after 171 days of composting have been observed for the lincomycin, trimethoprim, and macrolide families, and up to 64% removal for sulphonamides, tetracyclines, and quinolones (Zhang *et al.*, 2019), with norfloxacin, ciprofloxacin, and ofloxacin detected in the final compost product (Ezzariai *et al.*, 2018). Half-lives of antibiotics in compost vary from less than one day, recorded for certain penicillins (Boxall *et al.*, 2002), to over 2500 days for some quinolones (Ezzariai *et al.*, 2018).

Anaerobic digestion is a treatment process for solid organic wastes such as manure, used to generate methane-rich biogas and digestate fertiliser whilst reducing contaminants such as antibiotic residues and zoonotic pathogens (Turker *et al.*, 2018). However, similarly to composting, the removal of antimicrobials appears to be highly dependent on the antibiotic type, even within the same class of antibiotics:

some studies have demonstrated the significant removal of ampicillin, florfenicol, sulphadimethoxine, sulphamerazine, sulphamethoxazole, sulfameter, tetracycline, trimethoprim, and tylosin during anaerobic digestion; however, sulfamethazine, ionophores, and some degradation products of florfenicol and tylosin are more persistent (Congilosi and Aga, 2021). Many of these studies assess reductions in the parent compounds, but others have demonstrated the presence of antibiotic metabolites in digestate applied to soils (Rauseo *et al.*, 2019). Furthermore, antibiotic reductions may differ between the manure liquids and solids following anaerobic digestion (Wallace *et al.*, 2018), and the digestion process can be interrupted due to the presence of antimicrobials that can inhibit the microbial community (Shimada *et al.*, 2011).

Depending on the nature of the soil, antibiotics from manure, slurry, and anaerobic digestate applied to agricultural land can seep into the groundwater or enter surface water via run-off during heavy rainfall (Umwelt Bundesamt, 2018). In addition to the intentional application of sludge or manure to land as fertiliser, pharmaceuticals can enter the environment via leakage, flooding, and emergency overflow from manure storage tanks, septic tanks, and sewers (Suchowska-Kisielewicz and Nowogoński, 2021). Researchers in France found higher levels of animal-specific pharmaceuticals than human-specific products in watersheds during runoff events and periods of manure spreading (Jaffrézic *et al.*, 2017). Climate forecasts predict an increase in the intensity and frequency of torrential rainfalls due to climate change. Therefore, such incidents may become more common in the future, with negative impacts on water quality, public health, and the environment, in the absence of strengthened flood protection measures (Boxall *et al.*, 2009).

In terms of *AMR*, resistance determinants within human sewage are largely removed from the water effluent and enter the sludge fraction, as evidenced by studies of treatment plants in USA and China. These plants appear to reduce the abundance of resistance determinants in their water effluents by 2–4 orders of magnitude, but those in the biosolids are of the same order of magnitude as in the inflow sewage (Uluseker *et al.*, 2021).

Within animal husbandry settings, manure and any constituent resistance determinants are either deposited directly onto the land, or enter slurry/manure stores. The distribution of resistance determinants in soil environments may reflect the presence of antibiotic residues in slurry/manure, or resistant bacteria or genes in the effluent. Many studies have shown an increase in resistance genes in soils following manure amendment (Cycoń *et al.*, 2019); for example, Wepking *at al.* (2017) demonstrated a 5.2-fold greater abundance of β-lactam resistance gene ampC in dairy manure-exposed sites across the USA, compared to unexposed sites, potentially due to the use of cephalosporin antibiotics in dairy herds (Wepking *et al.*, 2017). Resistance can also arise in the absence of antibiotic selection pressure: researchers in USA observed the proliferation of resident AMR bacteria and genes encoding β-lactamases following application of manure from animals that had never previously received an antibiotic (Udikovic-Kolic *et al.*, 2014).

Within manure/slurry stores, it has been proposed that microbial populations are in a state of dynamic equilibrium, with microbial death balanced by fresh input. More specifically, storing dairy slurry without further input for at least 60 days has been predicted to reduce the spread of AMR bacteria onto the land, with a reduction of over 99% in cephalosporin-resistant *E.coli* (Baker *et al.*, 2022). The slurry tank is proposed as a natural surveillance point for on-farm resistance, as well as a critical control point for ameliorating the release of AMR determinants into the environment (Baker *et al.*, 2022).

As previously discussed, composting is sometimes offered as a potential strategy for reducing manure contaminants; however, the efficacy of the composting process in reducing *AMR concentrations* is disputed. Several studies have found that composting can reduce the levels of resistance genes by 50%–70% (Jadeja and Worrich, 2022), but it appears to be more effective at reducing resistant genes in chicken manure than pig and bovine manure (Qian *et al.*, 2018). Furthermore, others have reported an *increase* in the absolute abundances of sulphonamide, quinolone, and tetracycline-resistance genes (Jadeja and Worrich, 2022).

Similarly, the efficacy of anaerobic digestion in removing AMR determinants from animal manure is highly variable, and complete removal has rarely been observed

(Jadeja and Worrich, 2022). Some studies report an *increase* in resistance genes during the anaerobic digestion of manure from different origins (Agga *et al.*, 2020), but others suggest the process could significantly reduce their levels when thermophilic conditions (55°C) and long digestion times (>50 days) are deployed (Flores-Orozco *et al.*, 2020, 2022). Thermal pre-treatment, pre-treatment with activated carbon, and microwave pre-treatment have been found to reduce up to 95% of ARGs conferring resistance to sulfonamides, macrolides, and tetracyclines (Congilosi and Aga, 2021).

4.3.10 Fate in the environment

Following antibiotic consumption, metabolism, excretion, and disposal of human and animal waste, the first environmental compartments encountered by antibiotic-contaminated discharges are soil and water. The fate, bioactivity, and persistence (half-life) of antibiotics within soils depend on their propensity for degradation, sorption (binding to particles), and mobility (solubility) (Cycoń *et al.*, 2019). Mechanisms of antibiotic degradation in the environment include biodegradation by bacteria and fungi, and non-biotic processes such as hydrolysis, photolysis, oxidation, and reduction, dependent on physicochemical properties and environmental conditions (Polianciuc *et al.*, 2020). Volatilisation, adsorption, and non-extractable residue formation may also occur and contribute to the dissipation and sequestration of the active compounds, dependent on the surrounding soil properties. One study found significant and positive correlations between antibiotics with soil organic carbon and several heavy metals (i.e., Pb, Hg, and Ni), but a negative correlation with clay content (Wu *et al.*, 2023). Although sorption can impact the bioactivity of some antibiotics, other classes of sorbed antibiotics can remain largely bioavailable (Kong *et al.*, 2012). Elevated temperatures and aerobic conditions tend to expedite the degradation and transformation of antibiotic residues (Polianciuc *et al.*, 2020).

Studies have characterised the variability in behaviour of antibiotics based on interactions between these factors. For example, the half-lives of macrolides in soils can vary from 5 to over 120 days (Schlüsener and Bester, 2006), and tylosin tends to

mineralise or irreversibly bind to solid soil particles. Penicillins and cephalosporins have a high susceptibility to hydrolysis, which can occur within weeks in most surface waters or over several days in more alkaline systems (Längin *et al.*, 2009), and most of the fluoroquinolones have high chemical stability, are not easily degraded with increased temperature or by hydrolysis, and are rapidly transferred from water into the soil, sediments, and organic matter (Frade *et al.*, 2014; Goulas *et al.*, 2018). Depending upon the plant species and the antibiotic used, antimicrobial residues in soils can be taken up by crops, with phytotoxic, hermetic, or mutational responses (Tasho and Cho, 2016).

Antibiotic discharges from human and animal sources can also enter water systems, either directly from wastewater effluent or via soils. A large study from the University of York (Wilkinson *et al.*, 2022) screened for 61 active pharmaceutical ingredients in 258 of the world's rivers, including several in the UK. The most contaminated sites were in low- to middle-income countries associated with areas with poor wastewater and waste management infrastructure and pharmaceutical manufacturing; however, the UK's highest cumulative concentration (in ng/L) of active ingredients appeared in the 80th centile of all countries in the sample. Addressing water pollution concerns, the EU Water Framework Directive aims to maintain and improve the aquatic environment in the EU. It includes a Watch List of potential water pollutants that should be carefully monitored by Member States to determine the risk they present to surface water, and amoxicillin, ciprofloxacin, sulfamethoxazole, and trimethoprim are on the 2020 Watch List (Healthcare Without Harm, 2021).

Looking at the fate of AMR, resistant bacteria and genes have been detected in every environmental compartment on the planet, including in surface and ground waters, soils, and in the air/clouds, as well as in the microbiomes of people, domestic animals, and wildlife. An average concentration of 5,420 copies of resistance genes per metre cubed of cloud water has been detected, with researchers attributing higher concentrations of certain genes over continental Europe to antibiotic use in food-producing animals (Rossi *et al.*, 2023). A survey of faecal swabs from surfers from Britain found they were more likely to carry cephalosporin-resistant *E. coli* than non-surfers (Leonard *et al.*, 2018). AMR has also been detected in the microbiota of numerous wildlife species, including water voles, badgers, foxes, and wild birds,

including some long-distance migrants. Although wildlife populations closely associated with human populations are more likely to harbour clinically important AMR related to local human and farmed animal strains, AMR is still common in remote wildlife populations with little direct human influence (Arnold *et al.*, 2016).

Once antibiotic resistance determinants have entered the environment, their persistence depends on many factors, including the stability of the bacteria or gene, and the conditions of the local environment. Faecal bacteria from the microbiomes of people or farmed animals may be poorly adapted to the conditions prevailing in soils, and studies have demonstrated their demise in the environment to below detection level within weeks or months, depending on species and temperature (Jadeja and Worrich, 2022). Genetic elements, in contrast, can persist and move between environmental compartments regardless of cell viability (Chee-Sanford *et al.*, 2009). Land-use type, soil, and climatic factors affect ARG concentrations in the soil compartment: researchers found their abundance to be positively correlated with clay content, but negatively correlated with soil organic carbon, total nitrogen, mean annual precipitation, and metal elements (Wu *et al.*, 2023). Some may move between environmental compartments or microbiomes, for example from soils to surface or groundwater, or from soils to cultivated crops. Researchers analysed groundwater samples from urban locations in Romania, including in the vicinity of a swine farm, and together with antibiotic contaminants they detected genes conferring resistance to β-lactams, sulphonamides, tetracyclines, and macrolide-lincosamide-streptogramin B (Szekeres *et al.*, 2018). Studies have also evidenced the presence of resistance determinants on roots and leafy vegetables like pak choi, lettuce, radish, carrot, pepper, tomato, and maize (Chen *et al.*, 2019).

The presence of antibiotics is a major determinant for the selection of AMR in the environment, and one study found that over the course of two years of applying antibiotic-containing manure to a field, the prevalence of sulphonamide-resistant isolates increased (Hammesfahr *et al.*, 2008). Similarly, the presence of heavy metals such as chromium, copper, lead, zinc, and mercury found in inorganic fertilizers, manure, and wastewaters used for irrigation can contribute to the sustenance and transmission of AMR in soils, by selecting for co-resistance or cross-resistance of bacteria (Jadeja and Worrich, 2022). Some researchers have

suggested that manure plays a role in the amplification and dissemination of ARGs via mobile genetic elements to members of the soil microbiome (Jadeja and Worrich, 2022). Once a resistance determinant conferring a competitive advantage is expressed by a suitable host, the gene can be subject to replication within the resistome, illustrating the dynamic nature of resistance determinants as biological contaminants, in contrast to antibiotic residues as chemical entities that undergo eventual degradation in the environment.

4.3.11 Environmental impact of antibiotics and resistance determinants

Before a veterinary medicinal product is granted a Marketing Authorisation, it undergoes a detailed assessment of scientific data, including evidence on the quality, efficacy, and safety of the product as well as the risk of environmental contamination. In the UK, this process entails a strict regulatory approval process including an environmental risk assessment performed by the VMD. This independent scientific assessment reconciles the risks presented by a product based on its expected use, with its benefits to animal health and welfare. For example, the 2024 update to the UK Veterinary Medicines Regulations states that marketing authorisations will be refused if "*the active substance within the veterinary medicinal product meets the criteria for being considered persistent, bio-accumulative and toxic and the veterinary medicinal product is intended to be used in food-producing animals (except where it is demonstrated that the active substance is essential to prevent or control a serious risk to animal health)"* (UK Government, 2024b). When the benefit/risk evaluation is deemed positive, the product receives a Marketing Authorisation accompanied by specific measures for risk mitigation, which must be clearly stated on the product label.

However, within the range of authorised products available to prescribers and producers for use in farmed species in the UK, there is a diversity in their potential environmental impacts. These impacts vary according to the sensitivities of non-target organisms, the antibiotic class in use, and its exposure dose and time, and their mitigation is contingent upon close compliance with safety warnings expressed on product data sheets. Knowledge and awareness of environmental safety

measures amongst veterinary professionals and farmers is unknown; however, the environmental impact of veterinary medicines is an issue of growing concern, for example relating to parasiticides (Wall and Strong, 1987; BVA, BSAVA and BVZS, 2021; Perkins *et al.*, 2021; Sands and Noll, 2022; Wells and Collins, 2022).

Impacts based on the sensitivity of non-target organisms to antibiotics

At certain concentrations, many antibiotics are toxic to some non-target organisms, especially those occupying lower trophic levels within the food chain and representing principal primary producers of fundamental importance in ecosystems (Yang *et al.*, 2021). Although toxicity data is available for both terrestrial and aquatic environments, aquatic datasets are generally more complete (Boxall *et al.*, 2006), and provide a useful indication of the impacts of veterinary antibiotics that reach watercourses. Low-trophic level species such as cyanobacteria and algae exhibit higher sensitivity to many antibiotics than higher-trophic level organisms (e.g., crustacea and fish) (Yang *et al.*, 2021), and low concentrations of antibiotics can modify their growth, photosynthetic capability, and antioxidant systems (Yang *et al.*, 2021). Illustrating variable species sensitivities, macrolide tylosin has a 4 day-EC50 of 0.098mg/L (concentration required to exert a 50% effect on growth within 4 days) for cyanobacteria species *Aphanizomenon flos-aquae*, compared to a 4 day-EC50 of >86.57mg/L for algae species *Chlorella vulgaris* (Yang *et al.*, 2021).

Impacts on non-target organisms can also be non-lethal, affecting their metabolic functioning. One study found that standard courses of tetracycline in cows did not affect dung beetle numbers or survival, but did restructure dung beetle microbiota and increase greenhouse gas emissions from dung (Hammer *et al.*, 2016). Antibiotics at higher concentrations can also induce physiological changes and modify reproduction in fish, and can accumulate in plants, inhibiting or stimulating growth (Yang *et al.*, 2021). Further up the food chain, antibiotics are generally not toxic to humans or other vertebrates at clinical doses or less.

Impacts based on antibiotic class and exposure level

The toxicity of an antibiotic also depends on its *class*, and exposure *dose and time*. For example, macrolide antibiotics are more toxic to cyanobacteria and algae compared to other antibiotic groups, with EC50 values as low as <1mg/L (Yang *et al.*, 2021). For cyanobacteria *Anabaena* CPB4337, its 72-hour EC50 (bioluminescence) values range between 0.022mg/L for erythromycin, 6.2mg/L for tetracycline, and 56mg/L for amoxicillin (Yang *et al.*, 2021).

Because the concentrations of antibiotic residues in aquatic environments generally range from low ng/L to µg/L, authors Boxall *et al.* (2006) concluded that concentrations of veterinary antibiotics in the UK environment are likely to be below those that could affect aquatic and terrestrial organisms (Boxall *et al.*, 2006). However, the discharge and persistence of some compounds have given rise to hotspots of these compounds in the UK, relating to their proximity to human activities such as pharmaceutical manufacturing, hospital wastewaters, and farms, with potential unintended impacts on non-target aquatic organisms (Yang *et al.*, 2021). On a global basis, over 200 different pharmaceuticals have been reported in river waters, with some concentrations exceeding EC50 values, such as 6.5 mg/L for ciprofloxacin. Such effect concentrations classify the chemical as potentially very toxic to aquatic organisms, as described under the EU-Directive 93/67/EEC (Wilkinson *et al.*, 2022). The potential impacts of antibiotic toxicity to soil microbes on food production have not been fully explored and represent a research gap.

The impacts of AMR on ecosystems

Low concentrations of antibiotics – such as those found in some soil and aquatic environments - can select for AMR (Marti *et al.*, 2014; Yang *et al.*, 2021), and AMR determinants can affect the soil microbiome as well as organisms at all trophic levels within the ecosystem. Antibiotics at sub-inhibitory concentrations can function as signalling molecules and cause alterations in bacterial virulence, biofilm formation, quorum sensing, gene expression, and gene transfer (Andersson and Hughes, 2014). They can also modify bacterial enzyme activity, their ability to metabolise different carbon sources, their overall microbial biomass, and the relative abundance

of different species in microbial communities (Cycoń *et al.*, 2019). The impact of these changes on biodiversity, soil health, and food system resilience is poorly understood.

Research gaps also exist around the impacts of antibiotic residues and AMR on wildlife species occupying higher trophic levels within the food chain. As previously discussed, antibiotics appear to have low toxicity to vertebrates in general, although if AMU in humans and animals increases in the future, bioaccumulation within food webs and population impacts at lower trophic levels may cause negative consequences further up the chain. Diverse AMR genes have been found in many wildlife species studied across the world, including mealworms, cockroaches, wild boars, roe deer, coyotes, hedgehogs, badgers, foxes, and migratory wild birds (Dolejska, 2020; de la Torre *et al.*, 2021). Animals that tend to live near humans and seek food in cities, landfills, or areas with intensive agriculture, are more likely to carry AMR bacteria than those in areas with limited human footprints (Dolejska, 2020).

In the literature, wildlife species are often framed as *reservoirs* or *vectors* of resistant bacteria, representing *risks* of infection to humans and domestic animals (e.g., Lee *et al.*, 2022). The narrative regarding the impacts of resistant infections on wild animals themselves, i.e., consideration of AMR in terms of the value of wildlife, is lacking (Gomez *et al.*, 2022; Mitchell, 2023). Although most free-living wildlife are not *treated* with antibiotics, resistant bacteria may represent a health burden if they affect the microbiome over time (Bean *et al.*, 2024) or if their ARGs are associated with virulence. Therefore, the risks of AMR to biodiversity, bioabundance, and wild animal welfare warrant further attention.

4.3.12 The environmental footprints of antibiotics

The preceding subsections indicate that antibiotics and AMR determinants pose a risk to ecosystems at various trophic levels of the food chain. However, risks are likely to be highly variable in space and time, dependent on local human activities,

the type and concentration of antibiotics, the resistance determinants present, the local ecology, and environmental conditions.

To unravel these factors, assessments could take account of the two functions of environmental risk posed by antibiotic use: (1) *The estimated presence of antibiotics in the environment* – based on the quantities of use of the antibiotic, its excretion profile (i.e., percentage excreted), and its persistence (half-life) in the environment. Some reviews go further by estimating the propensity of the antibiotic to partition into different environmental compartments (such as sediment material and water) (Boxall *et al.*, 2006), although fragmented sorption data makes this more challenging to predict; and (2) Assessments could also account for *the potential impact of the antibiotic*, in terms of the concentration of the drug above which impacts on environmental organisms occur (expressed as the PNEC for the Environment, or PNEC-ENV), *and* the concentration above which selection for AMR occurs, with consequences for the environmental microbiome (expressed as PNEC-RES).

To construct a risk matrix depicting the environmental footprints of antibiotics and inform a One Health[18] approach to antimicrobial stewardship, data were sourced via literature review regarding the farmed animal usage of antibiotics in the UK by class (VMD, 2023b), their excretion profiles (% excreted in urine and faeces; Table 10), and their persistence (half-lives; Table 11). Together with EMA classifications of antibiotic risk to public health of increased AMR when used in farmed animal species (EMA, 2020), and environmental impact data (PNEC-ENV and PNEC-RES values from Bengtsson-Palme and Larsson, 2016; Tell *et al.*, 2019; Vestel *et al.*, 2022), these data were compiled and are presented in Table 12.

These databases in Table 10-12 are subject to certain limitations and assumptions. Data relating to excretion profiles and half-lives were fragmented in the literature, with limited data available for certain antibiotic classes. In addition, data were derived from studies with different research methods, species, and environmental sample types and conditions (see Tables 10 and 11) and should therefore be interpreted in

[18] One Health is an integrated, unifying approach that aims to sustainably balance and optimise the health of people, animals, and ecosystems. It recognises the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are closely linked and inter-dependent. (OHHLEP, 2020)

this context. To optimise accuracy, the estimated maximum environmental discharge in Figure 10 was calculated by multiplying the amount of each antibiotic sold for food producing animals in the UK in 2022, by the *maximum* percentage excreted by farmed animals found in the literature. This differs from the 'maximum residue' approach taken by the VMD and other authors (Boxall *et al.*, 2006) in their environmental impact assessments, which assumes that 100% of the medicines sold/used are discharged into the environment. Where a range of half-life values are expressed for an antibiotic class in Tables 11 and 12, the *maximum* value was used in Figure 10 to capture the estimated maximum persistence. Due to data availability, information regarding the partitioning of antibiotics into different environmental compartments (e.g., sediment, water) have not been included, and therefore persistence and impact data are likely to reflect a 'worst case scenario' for the classes that may undergo sorption and become partly non-bioavailable in certain environments. In short, the use of maximum half-life values and excluding the potential sorption effects of different soil types results in a worst-case illustration of ecological hazards in Table 12 and Figure 10. Indeed, the *actual* impact of some antibiotics on non-target organisms may be lower than indicated.

Table 10: Excretion profiles of antibiotics used in UK farmed animals. Percentage excretion values in **bold** represent the minimum and maximum in each class.

Antibiotic class	Active ingredient	% Excreted	**Sampling details** (species; route of administration; sample; chemical form excreted)	Reference
Tetracyclines	Oxytetracycline	**20**	Cattle; intra-muscular injection; manure; parent compound.	(Ince *et al.*, 2013)
		>80	Humans; unknown route; unchanged parent compound.	(Hirsch *et al.*, 1999)
	Chlortetracycline	75	Cattle; oral; faeces; parent compound.	(Elmund *et al.*, 1971)
		>70	Humans; unknown route; unchanged parent compound.	(Hirsch *et al.*, 1999)
	Doxycycline	<60	Various species; oral; in faeces; most is microbiologically inactive.	(EMA, 1997a)
		83-**96**	Laying hens; oral; faeces; parent compound.	(Peng *et al.*, 2016)
		>70	Humans; unknown route; unchanged parent compound.	(Hirsch *et al.*, 1999)
	Tetracycline	42-72	Pigs; oral; in faeces; unchanged parent compound.	(Winckler and Grafe, 2001)
		80-90	Humans; unknown route; unchanged parent compound.	(Hirsch *et al.*, 1999)
Penicillin	Amoxicillin	56-68	Laying hens; oral; faeces; parent compound.	(Peng *et al.*, 2016)
		80-**90**	Humans; unknown route; unchanged parent compound.	(Hirsch *et al.*, 1999)
	Ampicillin	**30**-60	Humans; unknown route; unchanged parent compound.	(Hirsch *et al.*, 1999)
	Procaine benzylpencillin	50-70	Humans; unknown route; unchanged parent compound.	(Hirsch *et al.*, 1999)
Aminoglycosides	Streptomycin	**50**	Humans; intravenous or intramuscular injection; in urine; parent compound.	(Buggs *et al.*, 1946)
		60-**80**	Dogs; oral; urine; parent compound.	(Stebbins *et al.*, 1945)
Macrolides	Tylosin	<50	Calves; intramuscular injection; faeces and urine; including active metabolites.	(EMA, 1997c)
		<100	Pigs; oral; faeces and urine; majority as metabolites with some activity.	(EMA, 1997c)
	Tylvalosin	74	Pigs; unspecified route; faces and urine; active metabolites.	(EMA, no date a)
	Erythromycin	>60	Humans; unknown route; unchanged parent compound.	(Hirsch *et al.*, 1999)
	Gamithromycin	<43	Sheep; sub-cutaneous injection; faeces and urine; parent compound and metabolites.	(EMA, 2016)
	Tilmicosin	40	Pigs; oral; parent compound.	(EMA, no date e)
	Tulathromycin	**30**-50	Pigs; oral; faeces and urine; parent compound.	(EMA, 2002)
		72-**100**	Pigs and cattle; unspecified route; urine and faeces.	(EMA, 2002)

Antibiotic class	**Active ingredient**	**% Excreted**	**Sampling details** (species; route of administration; sample; chemical form excreted)	**Reference**
Trimethoprim	Trimethoprim	80	Humans; oral; urine and faeces unmetabolised.	(EMA, 1997b)
		60	Humans; unknown route; unchanged parent compound.	(Hirsch *et al.*, 1999)
		<85-**89**	Rats and dogs; oral; in urine and faeces; some metabolised.	(EMA, 1997b)
Sulphonamides	Sulphadiazine	**42**	Pig; oral; sulphadiazine accounted for 44% of the 96% of excreted products.	(Lamshöft *et al.*, 2007)
	Sulphamethoxazole	**15**	Humans; unknown route; unchanged parent compound.	(Hirsch *et al.*, 1999)
Pleuromutilins	Tiamulin	**33**	Dogs; oral; faeces and urine; 100% excreted but 67% non-active metabolites.	(EMA, 1999b)
Lincosamides	Lincomycin	40	Rats; intravenous; parent compound.	(EMA, 1998c)
		32	Pigs; oral; faeces; parent compound.	(Kuchta and Cessna, 2009)
		91	Dog; oral; faeces and urine; majority unchanged lincomycin.	(EMA, 1998c)
Amphenicols	Florfenicol	**75**	Cattle; intra-muscular injection; some metabolites not microbiologically active.	(EMA, no date d)
		41	Broiler chickens; oral; 42% of 98.2% of total dose excreted as parent compound.	(EMA, 1999a)
		63-71	Rats and cattle; unknown route; some metabolites not microbiologically active.	(EMA, no date)
1st/2nd gen. cephalosporins	Cephapirin	<**98**	Dogs; intravenous injection; urine; includes parent compound and active metabolites.	(Cabana *et al.*, 1976)
		<**93**	Humans; intravenous injection; urine; includes parent compound and active metabolites.	(Cabana *et al.*, 1976)
Quinolones	Enrofloxacin	**99**	Broiler chickens; oral; faeces; main products are enrofloxacin and ciprofloxacin.	(Slana *et al.*, 2014)
	Ciprofloxacin[+]	45-52	Laying hens; oral; faeces; parent compound.	(Peng *et al.*, 2016)
		30-50	Humans; oral; urine and faeces; excreted as ciprofloxacin, a metabolite of enrofloxacin.	(EMA, 1998b)
	Danofloxacin	**14**-48	Pigs; intra-muscular injection; urine and faeces; unmetabolised danofloxacin.	(EMA, 1998a)
		>50	Rats, dogs and cattle; oral; urine; mostly unmetabolised parent compound.	(EMA, no date c)
	Marbofloxacin	57-60	Pigs; intravenous and intramuscular injection; urine; mainly parent compound.	(Schneider *et al.*, 2014)
3rd/4th gen. cephalosporins	Ceftiofur	**91-100**	Pigs; intra-muscular injection; urine and faeces; parent compound and active metabolites.	(Beconi-Barker *et al.*, 1996)
		95	Cattle and pigs; intra-muscular injection; most metabolised to active desfuroylcetftiofur.	(EMA, no date)
Polymyxins	Colistin	**61**	Rats; intra-venous injection; urine; parent compound and active metabolites.	(Li *et al.*, 2004)
		8	Dogs; intra-muscular injection; urine; 7.5% excreted as intact colistin.	(Al-Khayyat and Aronson, 1973)

[+] Ciprofloxacin is a human-only antibiotic but it is also a metabolite of enrofloxacin.

Table 11: Half-lives in soil, manure, and slurry, of antibiotics used in farmed animals in the UK. Half-life values in **bold** represent the minimum and maximum in each class.

Class	Compound	Half-life (days)	Conditions	Reference
Tetracyclines	Oxytetracycline	16 - 98	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
		1	Pig manure compost	(Wu *et al.*, 2011)
		10 - 31	Dairy/feedlot managed manure*	(Storteboom *et al.*, 2007)
	Chlortetracycline	18 - 58	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
		8	Pig manure compost	(Wu *et al.*, 2011)
		5 - 14	Dairy/feedlot managed manure*	(Storteboom *et al.*, 2007)
	Doxycycline	10 - 127	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
		120 - 533	Biosolids/soil	(Walters *et al.*, 2010)
	Tetracycline	12 - 62	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
		10	Pig manure compost	(Wu *et al.*, 2011)
		55 - 105	Pig slurry	(Winckler and Grafe, 2001)
		5 - 9	Ventilated/unventilated pig slurry	(Kühne *et al.*, 2000)
		120 - **578**	Biosolids/soil	(Walters *et al.*, 2010)
Penicillin	Amoxicillin	4	Manure	(Boxall *et al.*, 2006)
	Unspecified β-lactams	**5**	Manure	(Boxall *et al.*, 2002)
	Procaine benzylpenicillin	<**1**	Soil	(Boxall *et al.*, 2002)
Aminoglycosides	Streptomycin	<**30**	Soil	(Gavalchin and Katz, 1994)
	Unspecified	**30**	Unspecified manure	(Boxall *et al.*, 2002)
Macrolides	Tylosin	42	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
		<2	Aqueous phase of manure	(Loke *et al.*, 2000)
		19 - 23	Turkey manure/compost	(Dolliver *et al.*, 2008)
		3 - 8	Aerobic soil-manure mix	(Ingerslev and Halling-Sørensen, 2001)
		95 - 97	Soil	(Sarmah *et al.*, 2006)
	Tylvalosin	**0.4** - 35	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
	Erythromycin	6 - 52	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
	Gamithromycin	7 - 61	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
	Tilmicosin	11 - 104	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
	Tulathromycin	6 - **317**	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)

Class	Compound	Half-life (days)	Conditions	Reference
Trimethoprim	Trimethoprim	<60 - 100	Sediment	(Boxall *et al.*, 2002)
		26	Soil	(Lin and Gan, 2011)
		110	Soil	(Boxall *et al.*, 2006)
Sulphonamides	Sulphadiazine	**2** - 25	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
		12 - **237**	Cattle manure compost	(Cessna *et al.*, 2011)
		4 - 11	Soil + manure	(Zhang *et al.*, 2017)
	Sulphamethoxazole	9 - 59	Soil	(Lin and Gan, 2011)
		2 - 6	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
		18 - 24	Soil + manure-amended soil	(Albero *et al.*, 2018)
		5 - 12	Soil + manure	(Zhang *et al.*, 2017)
Pleuromutilins	Tiamulin	43 - **2000**+	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
		26	Soil	(Schlüsener and Bester, 2004)
Lincosamides	Lincomycin	95 - **2000**+	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
		9	Soil + manure-amended soil	(Albero *et al.*, 2018)
		17 - 19	Manure-amended soil	(Kuchta and Cessna, 2009)
		78 - 100+	Anaerobic manure lagoon	(Loftin, 2006)
Amphenicols	Florfenicol	**2** - **7**	Sediment	(Hektoen *et al.*, 1995)
1st/2nd gen. cephalosporins	Cephapirin	<**1**	Cattle slurry	(Li *et al.*, 2020)
Quinolones	Enrofloxacin	6 - 1751	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
		696	Soil	(Walters *et al.*, 2010)
	Ciprofloxacin+	**1** - 61	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
		1155 – **3466**	Biosolids/soil	(Walters *et al.*, 2010)
		<150 - 1700	Soils + organic waste	(Walters *et al.*, 2010)
	Danofloxacin	7 - 372	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
		87 - 143	Soil	(Boxall *et al.*, 2002)
	Marbofloxacin	5 - 205	Calf/pig/broiler manure	(Berendsen *et al.*, 2018)
3rd/4th gen. cephalosporins	Ceftiofur	**22** - **49**	Soil	(Gilbertson *et al.*, 1990)
Polymyxins	Colistin	**13** - **30**	Soil	(Peng *et al.*, 2022)

* Managed manure was subject to amending, watering, and turning.
+ Ciprofloxacin is not used in UK agriculture, but enrofloxacin is metabolised (in part) to ciprofloxacin.

Table 12: Summary of usage, excretion profiles, half-lives, and predicted no effect (PNEC) concentrations for ecological impact on non-target organisms (-ENV) and resistance selection (-RES), for the antibiotic classes in use in UK farmed animals.

Antibiotic class (in order of highest to lowest quantities used in 2022) Colour-coded based on EMA Category for use in animals[a]		LIKELIHOOD OF PRESENCE IN ENVIRONMENT				POTENTIAL IMPACT	
		Use in UK food animals, 2022[b]		**Percentage active ingredient excreted (%)**[c]	**Half-life** in slurry, manure, biosolids, compost, soil or sediment (days)[d]	**PNEC-ENV**[e] ***for class*** (µg/L; 5th centile)	**PNEC-RES**[f] ***for class*** (µg/L; 5th centile)
		Tonnes (% sold)	mg/Kg				
Tetracyclines		49.7 (32%)	8.3	20-96	1-578	**0.35**	0.6
Penicillins[g]		43.5 (28%)	7.3	30-90	1-5	0.58	**0.09**
Aminoglycosides		18.6 (12%)	3.1	50-80	30	**0.05**	0.21
Macrolides		14.0 (9%)	2.3	30-100	0.4-317	**0.03**	0.04
Trimethoprim-potentiated sulphonamides	Trimethoprim	14.0 (9%)	2.2	60-89	26-110	312	**0.5**
	Sulphonamide			15-42	2-237	**1.13**	13.2
Pleuromutilins		6.2 (4%)	1	33	26–2000	Unknown	**0.11**
Lincosamides (lincomycin)		4.7 (3%)	0.7	32-91	9–2000	**0.1**	1
Amphenicols		3.1 (2%)	0.5	41-75	2-7	Unknown	**1.35**
1st/2nd gen. cephalosporins		1.6 (1%)	0.1	93-98	1	0.12	**0.06**
Quinolones		0.6 (0.39%)	0.1	14-99	1-3466	0.66	**0.05**
3rd/4th generation cephalosporins		0.1 (0.07%)	0.02	91-100	22-49	0.12	**0.06**
Polymyxins (colistin)		0 (0%)	0	8-61	13-30	**0.5**	2
All		155.3 (100%)	25.7	8-100	0.4-3466	**0.05**[h]	0.06[h]

a EMA Categorisation of antibiotics for use in animals: Grey = Category D / 'Prudence' | Yellow = Category C / 'Caution' | Orange = Category B / 'Restrict' (EMA, 2020). | **b** Weight of antibiotics by antibiotic class sold for use in food-producing animals 2022, derived from UK VARRS Report + Supplementary Materials 1(VMD, 2023b; VMD, 2023c) | **c** Excretion profiles subject to non-systematic review and presented with references and details of sampling in Table 10. | **d** Half-lives equate to the time required to reduce to half of its initial quantity. Subject to non-systematic review and presented with references and details of sampling in Table 11. Note that the half-lives should be interpreted in light of varying propensities of antibiotics for sorption to sediments, which may render them partially non-bioavailable in some environments. | **e** PNEC-ENV = Predicted no-effect concentration for ecological toxicity to non-target organisms; values from Tell *et al.* (2019) and updated by Vestel *et al.* (2022). | **f** PNES-RES = Predicted No-Effect Concentration for antibiotic resistance selection; values from Bengtsson-Palme and Larsson (2016), derived from Minimum Inhibitory Concentrations from EUCAST database. The values for PNEC-ENV and PNEC-RES for each class reflect the upper 5th centile in order to identify the PNEC that would be protective with 95% confidence (Vestel *et al.*, 2022). The lower value of PNEC-ENV and PNEC-RES is in **bold text** for each antibiotic class, to identify the minimum concentration of the drug above which environmental impacts may occur. | **g** Pencillins are categorised as D/'Prudence' except for the aminopenicillins + beta-lactamase inhibitors (i.e., amoxiclav combinations), which are categorised as Category C / 'Caution' (EMA, 2020). | **h** These default PNECs for ENV and RES have been proposed by Vestel *et al.* (2022) for pharmaceutical site effluent, to capture safe limits for most antibiotic classes. The lower of these default targets - 0.05 µg/L - has been adopted by pharmaceutical industry coalition AMRIA as the target for manufacturing effluent (AMRIA, 2023a).

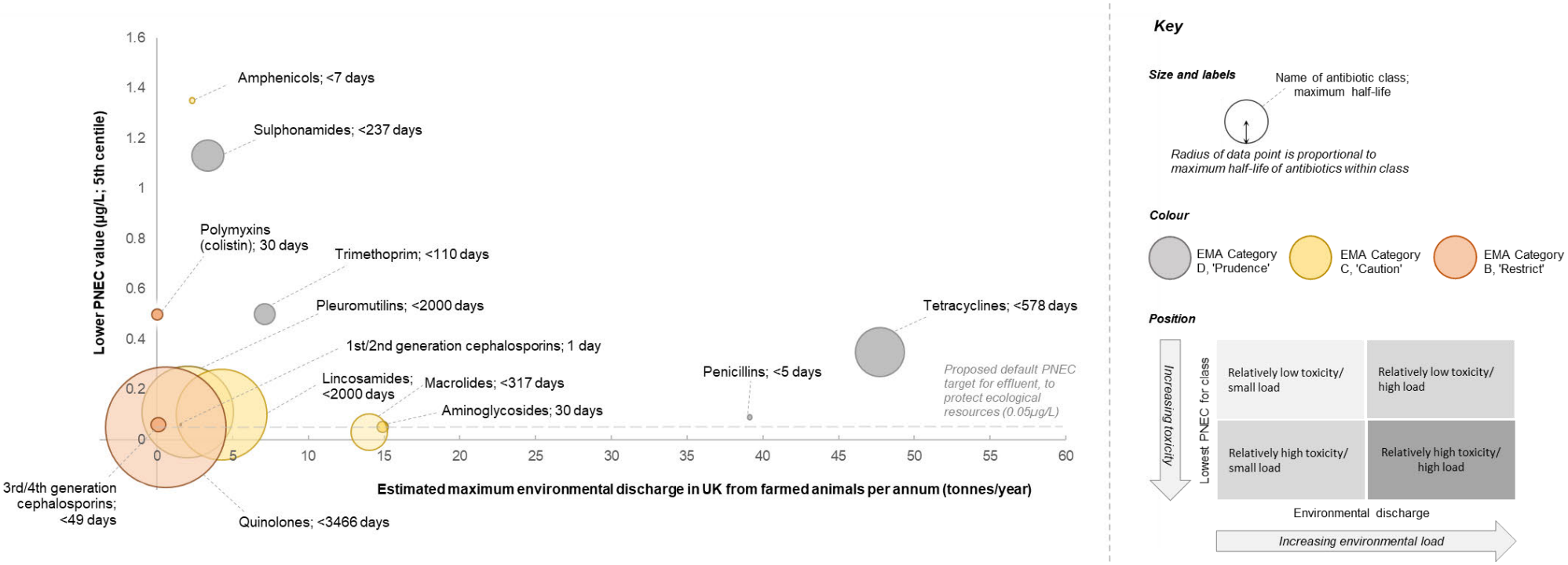

Figure 10: One Health Risk Matrix. Graphical illustration of the relative environmental footprints of antibiotic classes used in farmed animals in the UK, based on estimated environmental presence and potential ecological impacts. Data sources are cited in Tables 10-12. Estimated maximum environmental discharge (on x-axis) was calculated by multiplying the amount of each antibiotic sold for food producing animals in the UK in 2022 (VMD, 2023b) by the maximum percentage excreted by farmed animals. Lower PNEC values (on y-axis) are the lower of the PNEC-ENV and PNEC-RES (see Table 12) for each class, depicting the minimum antibiotic concentration above which environmental impacts occur (the lower the PNEC, the higher the toxicity). Maximum half-life values for each class are displayed as the radius of the data bubbles, to capture maximum persistence in the environment.

4.4 Discussion

Antimicrobial use in farmed animals is one of several anthropogenic sources of antibiotics in the environment. Many antibiotics pass relatively unchanged along the pathway from manufacturing to discharge, with risks of entry into the environment via antibiotic production, product disposal, application of animal slurry/manure on to agricultural land, and waste store overflows during flooding events. Antibiotic use in human patients contributes to the environmental burden and intersects with agricultural emissions, when human wastewater effluent and biosolids are applied to farmland.

Once antibiotics have entered environmental compartments such as soils or ground/surface water, low concentrations can present toxicity risks to non-target organisms and select for AMR within ecosystems. Levels of toxicity depend on the type and concentration of the antibiotic, and the non-target organisms present. However, antibiotics from some classes have PNEC-ENV values as low as 0.03µg/L above which negative environmental impacts occur. Organisms occupying lower trophic levels within the food chain and forming the bedrock of ecosystems such as algae, marine bacteria, and cyanobacteria are particularly susceptible to toxicity. Although in many places the concentrations of antibiotics in the UK environment are likely to be below those that could affect non-target organisms, the recurring discharge and persistence of compounds can create hotspots with unintended ecological impacts in the proximity of human activities, such as pharmaceutical manufacturing, hospital wastewaters, and farms.

Tables 10-12 and the risk matrix in Figure 10, depicting the environmental footprint of antibiotics used in UK farmed animals, provide more specific insights into the characteristics of the different antibiotic classes, which could inform antimicrobial stewardship with One Health objectives. Firstly, the farmed animal usage in the UK is well-aligned with public health goals, in that the classes deemed to present the *highest* risk of potential consequences to public health (EMA Category B (EMA, 2020); also known as Highest Priority Critically Important Antibiotics (HP-CIAs)) were used in the *lowest* quantities in 2022 (0.45% of total weight). Those presenting the

lowest risk to public health (EMA Category D) represented *most of* the total use (69% of total weight).

The data also show that when antibiotics *are* used, a large proportion are excreted as active ingredients or metabolites; for example, more than 90% of certain macrolides, cephalosporins, tetracyclines, quinolones, and lincosamides are excreted in urine and faeces. There does not appear to be any general differences between the EMA categories in terms of antibiotic excretion profiles. This portrays animal waste as a critical intervention point for One Health antibiotic stewardship.

Furthermore, once active ingredients are excreted and enter waste stores or soils, they can persist for variable durations from one day for some penicillins, tetracyclines, and cephalosporins, to over 2000 days for certain amphenicols, lincosamides, and quinolones (note the radius of the data bubbles in Figure 10). However, half-lives need to be interpreted considering the physicochemical properties of the antibiotic and its environmental conditions; for example, the highly persistent ciprofloxacin may be sequestered and rendered partially non-bioavailable in environments containing organic matter. These sorption profiles are not included in detail in this report due to variations in sorption potentials in different soil types. Persistence data could inform best practice manure and slurry management, for both indoor and outdoor-based production systems.

Figure 10 also indicates that antibiotic classes with the longest half-lives also have some of the lowest PNEC values, indicating that they persist for relatively long durations in the environment *and* exert environmental impacts at low concentrations. Pleuromutilins, lincosamides, and quinolones fall into this category. The cephalosporins, aminoglycosides, and macrolides also have some of the lowest PNEC values, but shorter half-lives. All of these classes are used in relatively low quantities in UK farmed species, and stewardship initiatives could aim to maintain or further reduce their usage, including in groups of animals, to minimise environmental concentrations.

The risk matrix shows that the penicillins and tetracyclines – which are assigned the lowest public health risk categorisation by the EMA - potentially impact

environmental organisms at relatively low concentrations *and* are likely to have the highest total environmental loads, owing to their relatively high usage. Indeed, tetracyclines are the most utilised antibiotic class in animal health globally (WOAH, 2022a). As such, there is a potential tension between public health and environmental objectives in the use of these classes, and antibiotic stewardship could maintain efforts to reduce and refine their use, and proactively address the most prevalent root causes for their application. There is potential for a similar tension to arise in the use of macrolides, which have recently been downgraded in their public health risk category by the WHO from 'highest priority critically important' to 'critically important' antibiotics for human health (WHO, 2024). There is therefore a risk that their use may increase in animal agriculture, which may present environmental concerns considering they have the lowest PNEC value of all the classes (0.03µg/L), and a half-life of up to 317 days.

The value of a default PNEC target of 0.05 µg/L (Vestel *et al.*, 2022) is illustrated in Figure 10**,** representing the environmental water concentration at which most antibiotic classes would not impact non-target organisms. Table 12 indicates that the lowest PNEC values for antibiotic classes within each EMA category are similar and varied, with lowest class values sitting between 1.35µg/L (amphenicols), and equal to or above 0.03µg/L (macrolides). In the absence of PNEC-ENV and PNEC-RES data for all antibiotics used in human and veterinary medicine, Vestel *et al.* (2022) suggest that antibiotic manufacturers employ a default conservative value of 0.05 µg/L as a target for pharmaceutical effluent that would decrease the selection pressure for antibiotic resistance and protect ecological resources. Similar soil/manure targets may also be useful, such as the EMA maximum threshold guideline of 0.1mg/kg for veterinary pharmaceutical residues in soils (EMA, 2008).

Figure 10 indicates that minimising the impact of antibiotic use in farmed animals may involve continued reduction in use, *and* measures to reduce downstream environmental concentrations - i.e., the position of antibiotics on the *x*-axis of Figure 10 is modifiable and can slide to the left with reduced use; and although the position of an antibiotic on the *y*-axis is *not* modifiable, it may be possible to reduce its environmental concentration at any one location to below the target default PNEC of

0.05 µg/L. This may entail solutions relating to use per animal unit, as well as population, stocking density, and production system transitions.

Finally, multiple research gaps were identified in this review. Further research is required around the environmental footprints of UK pharmaceutical manufacturing plants and non-UK facilities producing farmed animal antibiotics; antibiotic disposal practices amongst UK farmers; animal production system attributes associated with lower antibiotic usage and environmental discharge; levels of antibiotic residues and AMR within veterinary practice wastewaters; and the impact of antibiotic residues and AMR on wildlife, biodiversity, and soils.

4.5 Conclusions

Every antibiotic treatment event in farmed animals carries an environmental footprint, with considerable diversity in the duration and impact of that footprint. The UK agriculture sector has demonstrated significant progress in antimicrobial stewardship, and current usage patterns are well-aligned with the public health agenda, i.e., the classes in the highest public health risk category have the lowest use in farmed animal agriculture, including the quinolones, colistin, and 3rd/4th generation cephalosporins. Furthermore, the low usage of some classes aligns with an *environmental* agenda – i.e., the pleuromutilins, lincosamides, quinolones, macrolides, cephalosporins, and aminoglycides, which have low PNEC values and/or long half-lives.

However, there is a tension between public health and environmental objectives in the use of penicillins and tetracyclines – classes in the lowest public health risk category and with the highest levels of use, but with relatively low PNEC values. Tetracyclines can also have long half-lives of up to 578 days. If the use of macrolides increases in the future, a similar tension may arise, considering they have the lowest PNEC value of all the classes. In response, stewardship efforts could continue to reduce quantities of antibiotic use for all classes, and address concentration hotspots at sites of human activity, including farms. Stewardship initiatives could be reshaped

around One Health objectives, by maintaining or enhancing efforts to reduce the use of agents pertinent to the public health agenda, *and* those with ecological impacts, such as low PNEC values and long persistence characteristics, to address the identified tensions. Meanwhile, farmed animal welfare must remain paramount, with root cause solutions deployed to reduce the need for AMU. Attaining a threshold of 0.05µg/L in effluent from agricultural settings could complement and enhance the sector's stewardship efforts, with benefits spanning the One Health domains.

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Conflicts of interest statement

This chapter is based on a report commissioned to FAI Farms by RUMA Agriculture, and both organisations are affiliated with companies within the agricultural sector. However, the work was undertaken as a desk-based assignment independent of contributions from commercial entities.

4.6 Next steps

This chapter casts further light on the role of veterinary professionals within the sustainability agenda, in terms of the environmental impacts of their antibiotic use and prescribing in the farmed animal context. In line with the public health agenda, antimicrobial stewardship has been successfully managed in the UK in recent years (FAO and VMD, 2022), in-part due to veterinary interventions on farms. However, in some circumstances, pursuing positive outcomes for human and domestic animals in the absence of One Health decision making can pose health risks to ecosystems. This underscores the multiple and sometimes conflicting sustainability imperatives

requiring consideration in sustainable food systems, to balance and reconcile human, animal, and environmental wellbeing. In response to research questions 3 and 4, these conflicts represent a barrier to advancing antimicrobial stewardship as a facet of the broader sustainability agenda. Practical tools and guidance to aid One Health decision-making, such as Figure 10, could be crucial to support veterinary professionals and policy makers to navigate these conflicts.

The current chapter also touches on the difficulties in evaluating the performance of different farmed animal production systems, owing to the diversity in husbandry and management factors on farms and the range of desirable outcomes required by food businesses and citizens. With continuing debates around production systems and conflicting objectives identified as barriers to incorporating animal welfare and antimicrobial stewardship into the sustainability agenda, the next chapter tackles research question 4, regarding the actions that can be taken by veterinary and agricultural stakeholders. It demonstrates the use of a multi-criteria decision-making tool to incorporate neglected animal treatment metrics into evaluations of sustainability in commercial food supply chains. It then illustrates how regression analysis can be used to isolate the husbandry practices associated with the attainment of the highest sustainability scores, to inform future policy.

5. Benchmarking sustainability performance in UK free-range laying hen flocks

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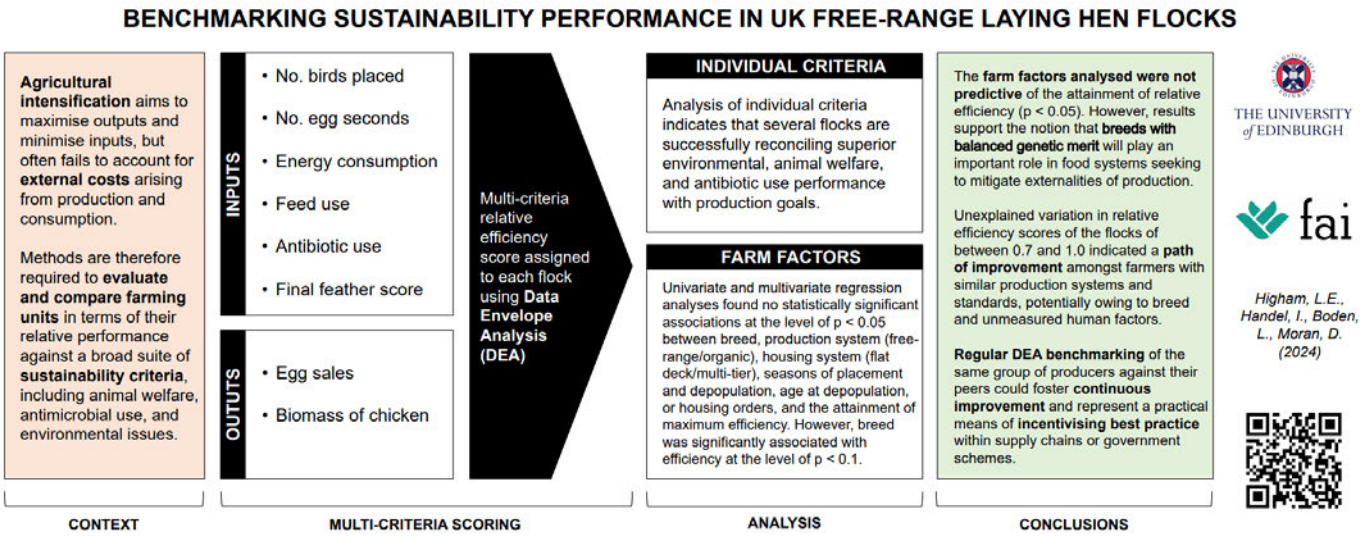
Highlights

- There is a need to evaluate the relative performance of farming systems in terms of multiple sustainability objectives.
- We benchmarked the performance of 80 free-range laying hen flocks using DEA to derive multi-criteria efficiency scores.
- Some flocks achieved superior performance across multiple sustainability objectives.
- Efficiency differences amongst farms with similar production systems are likely due to breed and unmeasured human factors.
- Benchmarking can incentivise best practice within supply chains or government schemes.

Graphical abstract



Abstract

CONTEXT: To equitably nourish the world's growing human population whilst halting further transgression of the planetary boundaries, there is a need to evaluate the relative performance of food and farming systems in terms of multiple and often competing food security, environmental, and ethical sustainability objectives.

OBJECTIVE: We aimed to benchmark the sustainability performance of 80 free-range laying hen flocks in England and Scotland, in production between 2016 and 2022, and to identify any common characteristics between the best performers to inform supply chain policy. Benchmarking was based on multi-criteria efficiency scores, incorporating six input and two output criteria covering human, animal, and environmental domains, including the neglected measures of animal welfare and antibiotic use.

METHODS: Data Envelope Analysis (DEA) was used to derive efficiency scores. Univariate and multivariate regression analyses were then applied to explore production factors that could be associated with the attainment of maximum efficiency.

RESULTS AND CONCLUSIONS: Approximately half of the flocks attained the maximum efficiency score, relative to their peers. Analysis of their component inputs and outputs demonstrated the favourable performance of the most efficient flocks across a broad array of criteria compared to inefficient flocks, indicating that some farms are successfully reconciling production and profitability with superior environmental, animal welfare, and antibiotic use performance. Univariate analysis and multivariate regression revealed no statistically significant predictors of efficiency at the level of $p < 0.05$, with unexplained variation in relative efficiency scores of the flocks of between 0.7 and 1.0, indicating a path of improvement amongst farmers with similar production systems and standards, potentially based on unmeasured human factors. However, univariate analysis revealed an association between laying hen breed and the attainment of efficiency at the level of $p < 0.1$, supporting the notion that breeds with balanced genetic merit will play an important role in food systems seeking to mitigate externalities of production.

SIGNIFICANCE: DEA allows multiple sustainability dimensions to be combined into a single performance metric to benchmark and compare production units. It offers a method for industry and government to identify potential leverage points to incentivise improved performance, and is a basis for better data collection in relation to both market and non-market (external) cost impacts of production, including animal welfare and antimicrobial use.

5.1 Introduction

Food production is increasingly central to the global sustainability debate, as society addresses the challenge of equitably nourishing a growing global population, whilst halting further transgression of the planetary boundaries (Richardson *et al.*, 2023). Agricultural intensification is one of several food system trajectories, with an aim to optimise resource use efficiency (i.e., maximising output per unit of input). However, in the pursuit of sustainability, intensification must include relevant external costs arising from production and, ideally, consumption. Such costs include greenhouse gas (GHG) emissions (Richie and Roser, 2020), air and water pollution (Air Quality

Expert Group, 2018; Evans *et al.*, 2019), animal welfare issues (McInerney, 2004), antimicrobial use and resistance (ECDC *et al.*, 2017), and poor mental and physical health (Parrón *et al.*, 1996; FAO, 2022). There is therefore a need to augment production efficiency metrics with information on the multiple environmental and ethical costs of production, i.e., metrics denoting human, animal, and environmental wellbeing.

Poultry production exemplifies the trade-offs between increased production and environmental and ethical goals in food systems. Egg production is an expanding global industry (FAO, 2020), yielding a cheap protein source from laying hens raised in a variety of systems, from backyard subsistence flocks to intensive caged colonies. The definition of 'good' production is contested, due to multiple and often conflicting sustainability goals. For example, caged systems aim to reduce labour and maximise production, but the restriction of bird behaviours through confinement raises animal welfare concerns (Scott, 2011; Nielsen *et al.*, 2023). In contrast, free range and organic systems afford behavioural opportunities for birds, and in some cases offer biodiversity and GHG benefits (Woodland Trust, 2019). However, organic systems are sometimes criticised for their relatively poor performance in terms of land use, biosecurity, and feed conversion efficiency (Mench and Rodenburg, 2018; Göransson *et al.*, 2023).

There is a need for methods to evaluate and compare farming units in terms of their performance against a broad suite of sustainability criteria, and one method is the linear programming technique Data Envelope Analysis (DEA). Building on a previous application of DEA to poultry production (Roskam *et al.*, 2020), this study uses production data to benchmark free-range laying hen flocks in their relative performance across several key sustainability domains. Free-range farming represents a potential means of achieving sustainability goals through sustainable intensification, which aims to increase yields and associated economic returns per unit time and land, whilst minimising negative impacts (Cassman and Grassini, 2020).

The aim is to use DEA to guide multi-criteria decision making and policy formulation for more sustainable food production. Responding to needs identified by Roskam *et*

al. (2020), Kyrgiakos *et al.* (2023), and Gajdács *et al.* (2021), we incorporate indicators of animal welfare, antimicrobial use, and environmental issues, as well as productivity, when estimating sustainability performance. While other studies have analysed the relation between technical efficiency and animal welfare (Hansen, 2023) or antibiotic use (Roskam *et al*., 2020), to our understanding this study represents the first attempt to embed animal-based welfare indicators and antibiotic use as inputs in DEA.

The following section provides an overview of the data and the methodological approach including DEA, univariate analysis, and multivariate regression. Section 5.3 presents the resulting flock efficiency scores and the performance of their composite inputs and outputs. It then demonstrates how statistical analysis can be used to scrutinise the farm factors associated with operationalising maximum relative efficiency. Sections 5.4 and 5.5 discuss the results and conclusions, respectively. Overall, our study aims to (a) highlight the need to include animal treatment dimensions into multi-criteria sustainability evaluations; (b) demonstrate how this can be achieved with commercial datasets; and (c) illustrate how such analyses can support continuous improvement and policy making, by identifying associations between best performance and modifiable practices.

5.2 Materials and methods

5.2.1 Data

We used a commercial dataset consisting of production characteristics and outcome measure data for over 500 laying hen flocks from 82 independently-owned free-range and organic farms in the UK and Republic of Ireland. The farms supply a single egg packing company in England. After data cleaning to include only the flock records featuring the full set of variables selected for this study, the sample size decreased to 80 flocks from 17 farm sites in England and Scotland. The clean dataset fulfilled the general rule for DEA that the number of decision-making units

(i.e., 80 flocks) should be at least three times larger than the total number of input and output variables (8 variables in total).

The flocks were placed and depopulated over a six-year period between November 2016 and October 2022. A flock is defined for the purpose of this study as a group of laying hens placed, housed, and depopulated together, and the farms in the sample frequently had multiple flocks in production simultaneously in different houses. The 80 flocks represented 722,199 birds placed, producing over 225 million eggs over the study period, worth over £17.6 million in producer income.

The data were primarily obtained from a commercial hardware monitoring system called BirdBox (Food Animal Initiative (FAI)) installed inside layer houses, which collates environmental and animal sensor data as well as measurements manually entered by farm staff. Animal welfare data (feather scores) were separately supplied by the egg packing company. The data were originally collected as commercial records and not for research purposes, hence they contain certain limitations: the included criteria were contingent upon and constrained by their availability within the dataset, which did not include some desirable metrics such as carbon footprint; they only included metrics relating to the laying stages and not the rearing stages of the layer life cycle; they were subject to missing data; and some data for each flock were manually entered by different farm workers and therefore may be subject to inconsistencies between flocks. Furthermore, the flocks were sampled from a relatively homogenous, high welfare strata of the UK laying hen flock (i.e., free-range and organic) and only included flocks with a full complement of relevant variables. Therefore, the sample reflects a cohort of farms with relatively high welfare standards and diligent data management practices, so is unlikely to represent the standards, challenges, or variation in performance within the wider population. To address some of the missing data, standard industry data were imputed for a limited number of flocks and variables.

5.2.2 Variables

Variables for this study were selected based on their representation of human, animal, and environmental objectives, and their availability within the commercial dataset. Data for each flock were imported from Excel (Microsoft 2016) workbooks derived from the hardware system into R, in which relevant metrics from each flock were extracted to form a new data object. Available variables of relevance to egg and meat production, environmental impacts, and animal welfare together with flock identifiers and characteristics were selected or computed for the study dataset (Tables 13-14). A second dataset provided by the egg packing company detailing final feather scores at 70 weeks (assessed using the AssureWel Protocol; see Table A in the Supplementary Materials) were joined to the study dataset, matched using farm and flock code identifiers. Missing values for feed consumption or bird weight at depopulation were imputed for 27 flocks, from publicly available breed specifications based on flock breed and age.

Six variables were selected as 'inputs', and two as 'outputs' for use in DEA (Tables 13 and 14). Inputs are variables to be *minimised* for increased relative efficiency (i.e., costs), and include indicators of resource use, food waste, antibiotic use, and animal welfare issues. Output variables to be *optimised* for increased relative efficiency include indicators of food production and economic performance. Table 15 shows additional indicators derived from the input and output variables that were not used in the DEA computation, but used to support the characterisation of the most relatively efficient flocks.

Although flocks from the same farm are not independent, flock was still considered the most appropriate unit for analysis. Production characteristics of flocks on each farm changed over the course of the six-year period of study, and assigning farm as the unit for analysis would necessitate the aggregation of data for multiple flocks, diminishing data granularity. While flocks were maintained as the unit for analysis, mean relative efficiency scores were also presented by farm.

Table 13: Input variables used in DEA.

Input variable	Definition and sustainability implications
Number of birds placed	Number of pullets placed in the layer house at the beginning of the flock cycle. The number of hens used has environmental resource use, economic, and animal welfare implications.
Flock total number of egg seconds	Total number of egg seconds produced by the flock between placement and depopulation (farm seconds only, excluding those downgraded due to breakage *etc.* at the factory). Considered an economic cost of production due to the downgrade in egg value with quality, with environmental relevance due to resource use and food waste.
Flock energy consumption [MWh]	Energy use for lighting and feed augers in the house between flock placement and depopulation; excludes energy use for house ventilation. Of economic and environmental relevance.
Flock antibiotic use [% bird days medicated]	Calculated as: $100\ x\ \frac{Sum\ of\ no.of\ hens\ in\ flock\ on\ each\ day\ the\ flock\ was\ medicated\ with\ antibiotics}{Sum\ of\ no.of\ hens\ in\ the\ flock\ on\ each\ day\ of\ production}$ Of public health, animal welfare, environmental, and economic relevance, due to antimicrobial resistance risk, indication of disease, cost of medicines, and environmental impact of residues.
Flock total feed consumption [Kg]	Total feed intake by the flock from placement to depopulation. Derived from feed bin sensors. Of economic and environmental relevance (land and resource use).
Final (70 week) feather score	Flock feather score at 70 weeks of production, according to the AssureWel Protocol scale 0-3 (see Table A, Supplementary Materials). 50 randomly selected hens per flock were scored manually by farm staff, and the mode score was assigned to the flock. In the event of an equal number of hens receiving two different mode scores, the lowest (best) score is taken. Indicator of animal welfare due to association with feather pecking.

Table 14: Output variables used in DEA.

Output variable	Definition and sustainability implications
Flock total egg sales [£]	Estimated packer-to-producer egg sales income, calculated as: $\frac{(Total\ number\ of\ eggs\ produced\ by\ flock\ \mathrm{x}\ price\ in\ pence\ per\ egg)}{100}$ Egg production relates to the period between placement and depopulation. Price per egg was calculated from industry data[+] as the average egg price (per dozen divided by 12) over the whole study period for free range (7.45p/egg) and organic (12.11p/egg) eggs. Prices were then allocated to each flock based on their system of production. Prices do not include any downgrade in the value of egg seconds. Indicator of food production and economic performance accounting for the organic price premium.
Total flock biomass of chicken delivered [Kg]	Sum of bodyweights of hens delivered to slaughterhouse. i.e.: $Mean\ hen\ weight\ at\ depopulation\ \mathrm{x}\ no.of\ hens\ depopulated$ Indicator of food production and economic performance.

[+] Average egg prices for the study period were calculated for free-range and organic eggs using data derived from (DEFRA, 2023). Organic egg prices were not publicly available for the study period; therefore, the average proportional price difference between free-range and organic eggs was calculated for the period Q1 2006 – Q4 2011 (the only period for which data were available), and this difference (1.63) was applied to the average free range egg price during the study period to estimate an average organic egg price.

Table 15: Additional variables computed from the input and output variables in Tables 13 and 14.

Characteristic	Definition and sustainability implications
Egg production per hen day [eggs/hen day]	Calculated as: $\frac{Total\ egg\ production\ by\ the\ flock}{Sum\ of\ no.of\ hens\ in\ the\ flock\ on\ each\ day\ of\ production}$ Indicator of food production and economic performance, normalised for the flock size; otherwise referred to in the industry as % hen-day.
Flock percentage egg seconds [%]	Percentage of total eggs downgraded to farm seconds (i.e., not including downgrades to factory seconds due to damage during processing): $100\ x\ \frac{No.egg\ seconds}{Total\ number\ of\ eggs\ produced}$ Considered an economic cost of production due to the downgrade in egg value, with environmental relevance due to resource use and food waste. Normalised for total egg production.
Feed conversion efficiency [g feed/egg]	Calculated as: $\frac{Total\ feed\ consumption}{Total\ egg\ production}$ Indicator of economic and environmental performance (land and resource use), per unit of food produced.
Flock total mortality [%]	Calculated as: $100\ x\ \frac{(No.birds\ placed - no.hens\ depopulated)}{No.birds\ placed}$ Indicator of economic costs and animal welfare performance, with environmental relevance due to resource use and food waste.

5.2.3 Data Envelope Analysis (DEA)

DEA, an extension of linear programming, is a non-parametric technique of frontier estimation introduced by Charnes *et al.* (1978) building on work by Farrell (1957), enabling the measurement of relative efficiency and benchmarking of comparable decision-making units (DMUs) (Mobtaker *et al.*, 2012). The DMUs can be any production entities such as companies, farms, herd/flocks, shops, clinics, projects, or individuals that transform the same resources into products or services, and whose success is defined by multiple outcomes, as opposed to a single objective such as profit maximisation (Bogetoft and Otto, 2011a,b). For example, one flock could be one DMU, and could be benchmarked alongside other flocks (DMUs) in a group. DEA essentially involves an efficiency calculation of output per input, but in contrast

to conventional two-dimensional efficiency calculations (such as feed conversion efficiency), it allows the inclusion of multiple outputs and multiple inputs. Because DEA 'scores' DMUs based on an outputs/inputs ratio, any units of measurement can be used for the individual criteria, and they do not need to be normalised according to the size of DMU prior to analysis. The method has been applied in many agricultural, sustainability, and business settings (Barnes *et al.*, 2011; Mobtaker *et al.*, 2012; Zhou *et al.*, 2018; Long *et al.*, 2020; Roskam *et al.*, 2020), and here is used to derive multi-criteria relative efficiency scores for comparable laying hen flocks (each representing individual DMUs).

More specifically, the DEA method computes a relative technical efficiency score for each DMU, based on an optimised ratio of its weighted outputs over weighted inputs, subject to the condition that scores for all DMUs are less than or equal to one (Mousavi-Avval *et al.*, 2011; Zhu, 2014). The weights for each DMU are individually allocated based on the combination of weights, inputs, and outputs that will maximise the relative efficiency score for that DMU; therefore, each score reflects a DMU's individual strengths in comparison to its peers. Scores are calculated as a comparison to the best performing unit in the group, rather than to the average performance of the group (Mousavi-Avval *et al.*, 2011) or an external benchmark, and they indicate how efficient a DMU is in utilising inputs to produce outputs at a certain level, relative to its peers. This analysis constructs a theoretical piecewise linear frontier or 'envelope' over the observed data points, which is assembled by solving a linear programming problem for each DMU in the sample (Barnes *et al.*, 2011). Attaining the maximum relative efficiency score of one implies that the DMU is a best performer within the sample, and is located on the so-called production frontier (Mousavi-Avval *et al.*, 2011). The mathematical notation for DEA is provided in the Supplementary Materials.

In DEA, the model can be either 'input oriented', in which the inputs are minimised under the same output levels, or 'output oriented', in which outputs are maximised with similar input levels (Malana and Malano, 2006). In the input orientation, relatively inefficient DMUs can be made efficient by reducing the input levels while holding the outputs constant. A farmer generally has more control over input than output levels, and in this study, reducing costs in terms of animal welfare, the

environment, and resources for given outputs is prioritised over maximising production. Therefore, the input-oriented approach was selected.

DEA can follow the Charnes, Cooper, and Rhodes model (CCR), which provides for constant returns to scale (Charnes *et al.*, 1978), and assumes the DMUs are operating at their optimal sizes having evolved in a perfectly competitive environment (Huguenin, 2012). The CCR model decomposes the relative technical efficiency into 'pure technical efficiency' for management factors and 'scale efficiency' for scale factors (Mobtaker *et al.*, 2012). The alternative Banker, Charnes, and Cooper model (BCC) on the other hand, assumes variable returns to scale (Banker *et al.*, 1984) when firms face imperfect competition, and only compares units to others of a similar size (Galanopoulos *et al.*, 2006). We used the BCC (variable returns to scale) model to generate the relative efficiency scores to account for differing farm and flock sizes, but CCR was also computed to assess scale efficiency. Scale efficiency is an additional output of DEA that establishes whether the efficiency of each DMU is constrained by its size. If its efficiency could be improved by increasing or decreasing the DMU size (i.e., number of birds placed), they are identified as "small" or "large" respectively, with the remaining DMUs considered to be operating at optimum size for relative efficiency.

Slacks are also calculated in DEA and are a feature of some DMUs, when a reduction in one of the inputs is possible without increasing any of the others, whilst still producing the same level of output. These DMUs are said to be relatively technically efficient under the 'Farrell' definition; however, 'Pareto-efficiency' is attained when no further decrease in any input is feasible without an increase in at least one other input (Galanopoulos *et al.*, 2006). The most relatively efficient units are those that are Pareto-efficient, i.e., have a technical efficiency score of one *and* zero slacks, therefore this definition is used to identify flocks as relatively 'efficient' in this study.

The first stage of analysis involved implementing DEA on the study database using the Benchmarking package in R (Bogetoft and Otto, 2022a,b; R Core Team, 2022) to compute a relative efficiency score, slacks, and scale efficiency for each laying hen flock. Relative efficiency scores were plotted as both continuous and categorical

variables (efficiency score = 1 / efficiency < 1) against the input and output variables and derivatives (see Tables 13-15), to demonstrate the composition of their efficiency scores.

5.2.4 Regression analysis

DEA relative efficiency scores were used to explore the characteristics of the most efficient flocks, illustrating how this method can inform best practice and guide policy. To elucidate any associations between production system characteristics and attainment of the maximum efficiency score, univariate analysis and multivariate regression were performed in R. Relative efficiency was assigned as a categorical response variable for each flock, and explanatory variables are displayed in Table 16. Table B in the Supplementary Materials describes the differentiating features of free range and organic systems.

Table 16: Flock and production characteristics used as explanatory variables in regression analysis of relatively efficient flocks.

Characteristic	Definition
Seasons of placement and depopulation	Seasons in which the flock was placed and depopulated: between April and September (inclusive) = summer; between October and March (inclusive) = winter.
Age at depopulation	Age of the hens at depopulation, in days
Production system	Laying hens produced to free-range or organic standards (see Table B, Supplementary Materials)
Housing order	Flock subject to an avian influenza housing order during the production cycle (yes/no); duration of housing orders (in days). Housing order dates obtained via a Freedom of Information request to the UK Government in March 2023.
Breed	Breed of laying hens, assigned codes A, B or 'Other'
Housing system	Internal housing structure: flat-deck (where there is a litter floor plus one raised level of slats that contains perches, feeders, drinkers, and nest boxes) or multi-tier (where there is a litter floor plus up to four raised levels that contain the other resources, with manure belts under each level).

Fisher's Exact Test and t-tests were used in univariate analyses to determine whether individual explanatory farm and production variables were predictive of a flock achieving the maximum relative efficiency score. To account for the multiple

farm and production factors involved, multivariate models were then constructed, and corrected Akaike Information Criterion (AICc – a complexity penalised measure of model fit) used to select the model of best fit. The final model was selected, allowing review of p-values and confidence intervals in light of biologically plausible associations.

5.3 Results

5.3.1 Efficiency and scale

Relative efficiency scores were derived using DEA for the 80 flocks. The mean relative efficiency score was 0.955 (minimum: 0.7211; maximum: 1.000). Of all 80 flocks, 39 (48.8%) achieved the maximum efficiency score of one, however after identification of slacks for one of these flocks, 38 were classified as pareto-efficient and were thereafter assigned as relatively 'efficient' flocks. Relatively 'inefficient' flocks included 26 (32.5%) achieving scores of $\geq$0.9 and <1; 13 (16.2%) with scores of $\geq$0.8 and <0.9, and the remaining 2 flocks (2.5%) attained efficiency scores of $\geq$0.7 and <0.8. Table 17 shows the scores grouped by farm, demonstrating how the farms themselves can be ranked. All but one farm produced at least one relatively 'efficient' flock.

Scale efficiencies were computed for the flocks, and flocks grouped by scale. Flocks facing increasing returns to scale are considered 'small' – these flocks could increase their relative efficiency by increasing flock size. Conversely, flocks facing decreasing returns to scale are considered 'large' and could increase their efficiency score by decreasing flock size. Results indicated that 27 flocks were defined as too 'small' and had a mean flock size of 6,919 birds placed; 29 flocks were identified as 'optimum' in size with a mean flock size of 9,203 birds placed; and 24 flocks were classified as too 'large' with a mean flock size of 11,188 birds placed.

5.3.2 Performance of input and output criteria

Relatively efficient and inefficient flocks were then compared in terms of the performance of each input and output variable and their derivatives, in order to demonstrate the composition of the efficiency scores. Figure 11 displays the continuous input and output variables for relatively efficient and inefficient flocks. Table C in the Supplementary Materials contains the data relating to Figure 11. Figure 12 presents the efficiency scores as a continuous variable plotted against continuous inputs and outputs. Table D in the Supplementary Materials presents the relative efficiency score against feather score, as categorical variables**.**

5.3.3 Predictors of relative efficiency

Tables 18 and 19 present the proportions, upper and lower confidence intervals and p-values derived using Fisher's Exact tests and t-tests to explore associations between individual farm and production factors and flock relative efficiency scores. Table 20 displays the results of multivariate regression models with AICc scores, identifying the model "Categorical Housing Order" as the model with the lowest AICc score indicative of best fit (Burnham and Anderson, 2002).

Table 17: Summary of 17 laying hen farms in England and Scotland, in terms of the number of flocks included in the study, the number and proportion of flocks attaining the maximum relative efficiency score, and the mean relative efficiency score for each farm, determined using DEA.

	Farm code	No. flocks	No. efficient flocks	Prop.	Mean efficiency score
	A	1	1	1.00	1.00
	B	4	4	1.00	1.00
	C	3	2	0.67	1.00
	D	3	2	0.67	0.99
	E	3	2	0.67	0.99
	F	4	3	0.75	0.98
	G	3	2	0.67	0.96
	H	4	2	0.50	0.96
	I	6	2	0.33	0.96
	J	4	2	0.50	0.95
	K	16	7	0.44	0.95
	L	10	3	0.30	0.95
	M	3	2	0.67	0.94
	N	5	2	0.40	0.94
	O	3	1	0.33	0.94
	P	3	0	0.00	0.92
	Q	5	1	0.20	0.88
Total	—	80	38	—	—

Prop. = proportion of flocks that are relatively efficient | Proportion of all flocks that are relatively efficient = 0.475 | Mean relative efficiency score for all flocks = 0.955

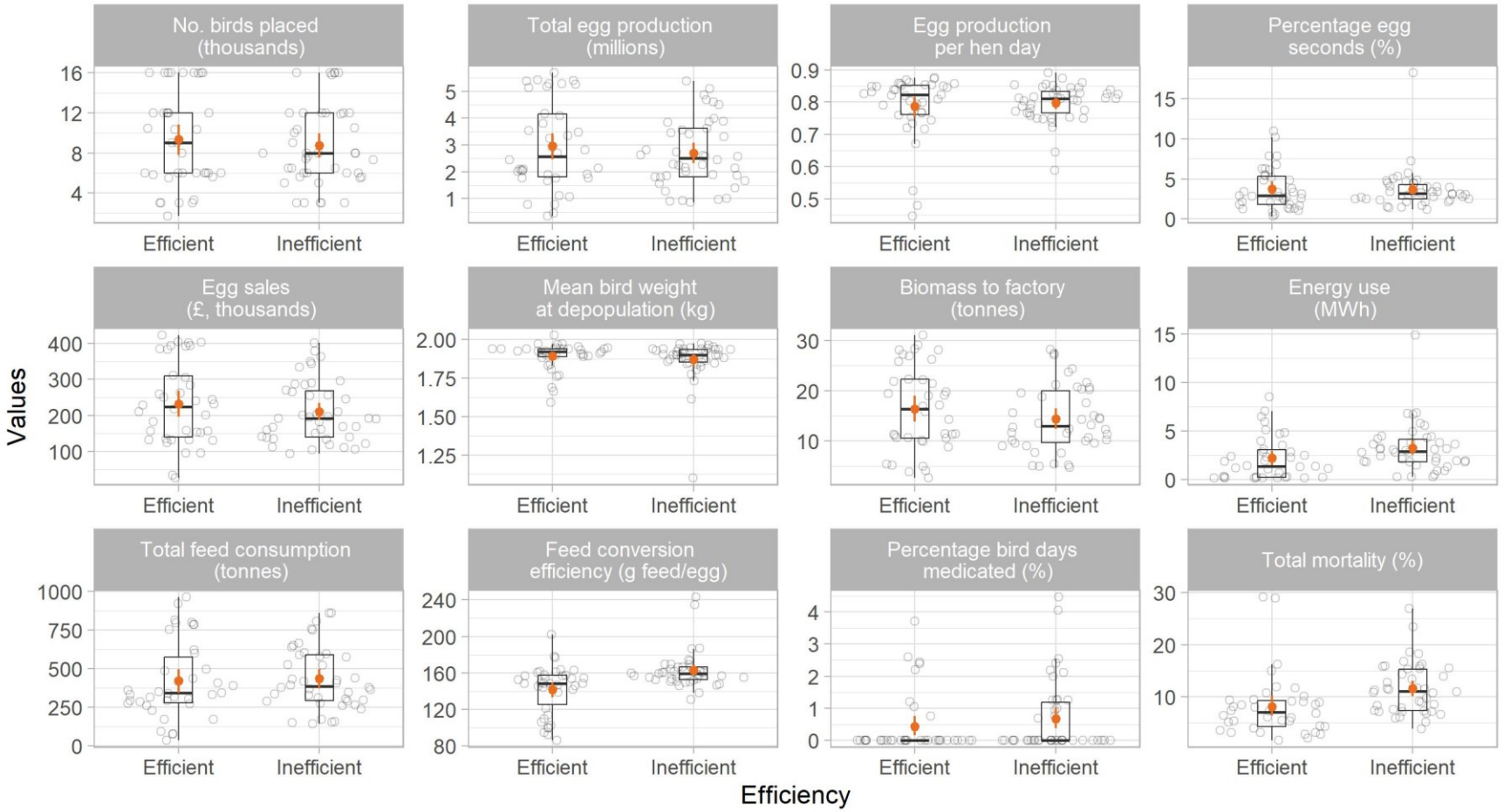


Figure 11: Performance of 80 relatively efficient and inefficient laying hen flocks in England and Scotland determined using DEA, in terms of composite continuous criteria. Grey circles in the scatter plots represent continuous variables for each flock; box-and-whisker plots illustrate median and upper/lower quartile ranges; orange point-and-whisker plots represent mean and lower/upper 95% confidence intervals.

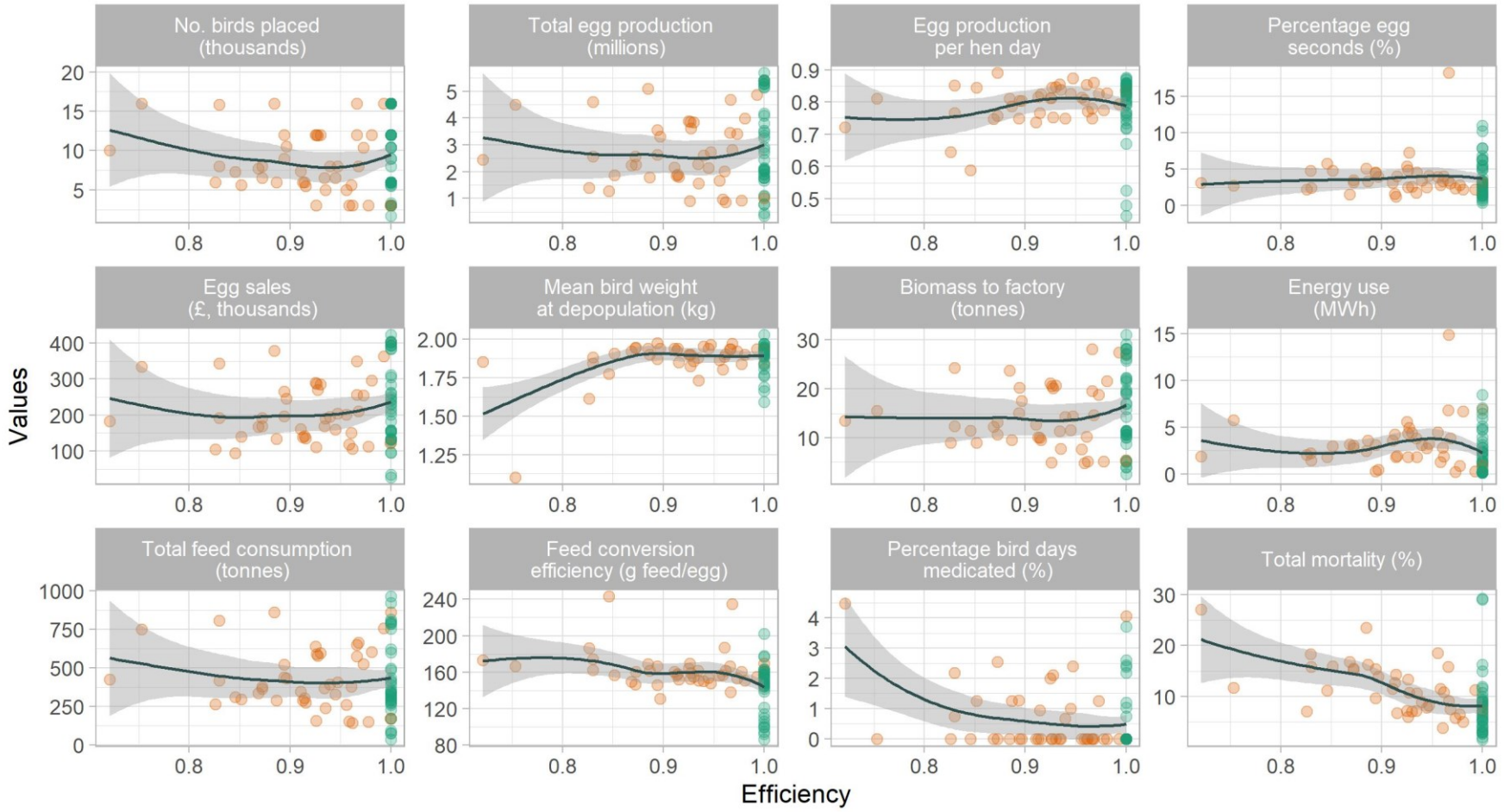


Figure 12: Performance of 80 laying hen flocks in England and Scotland, in terms of relative efficiency score determined using DEA and composite continuous criteria. Orange and green circles in the scatter plots represent continuous variables for each relatively inefficient and efficient flock, respectively; dark grey lines and grey shading represent a line of best fit with 95% confidence intervals.

Table 18: Associations between individual farm and production factors and the attainment of maximum relative efficiency scores determined using DEA, amongst 80 laying hen flocks in England and Scotland.

Variable	No. flocks	No. relatively efficient flocks	Prop. (lci-uci)
Breed (Reference level – Breed A; p = 0.0822*)			
A	19	11	0.58 (0.33 - 0.8)
B	58	24	0.41 (0.29 - 0.55)
Other	3	3	1 (0.29 - 1)
Housing system (Reference level – Flat Deck; p = 0.4633)			
Flat Deck	58	26	0.45 (0.32 - 0.58)
Multi-tier	22	12	0.55 (0.32 - 0.76)
Production system (Reference level – Free Range; p = 1.0000)			
Free range	66	31	0.47 (0.35 - 0.6)
Organic	14	7	0.5 (0.23 - 0.77)
Subject to housing order (Reference level – No; p = 0.1162)			
No	42	16	0.38 (0.24 - 0.54)
Yes	38	22	0.58 (0.41 - 0.74)
Season of depopulation (Reference level – Summer; p = 0.5115)			
Summer	41	21	0.51 (0.35 - 0.67)
Winter	39	17	0.44 (0.28 - 0.6)
Season of placement (Reference level – Summer; p = 0.8214)			
Summer	46	21	0.46 (0.31 - 0.61)
Winter	34	17	0.5 (0.32 - 0.68)

Prop. = Proportion of flocks scored as relatively efficient | lci = lower 95% confidence interval | uci = upper 95% confidence interval | * = statistically significant at the level of p<0.1

Table 19: Associations between individual farm and production factors, and the attainment of maximum relative efficiency scores determined using DEA, amongst 80 laying hen flocks in England and Scotland.

Variable	n	Mean (lci-uci)
Age at depopulation (days) (p = 0.827)		
Efficient	38	517.39 (506.96 - 527.83)
Not efficient	42	518.76 (511.65 - 525.88)
Duration of housing orders (days) (p = 0.549)		
Efficient	38	56.32 (35.5 - 77.13)
Not efficient	42	47.52 (26.55 - 68.5)

n = no. of flocks | lci = lower 95% confidence interval | uci = upper 95% confidence interval

Table 20: Multivariate regression exploring associations between farm and production factors, and the attainment of maximum relative efficiency scores determined using DEA, amongst 80 laying hen flocks in England and Scotland. With the lowest AICc score, "Categorical Housing Order" is the model of best fit.

	Original			Categorical housing order			Categorical housing order and age			Categorical age at depopulation		
Predictors	*Odds Ratios*	*CI*	*p*	*Odds Ratios*	*CI*	*p*	*Odds Ratios*	*CI*	*p*	*Odds Ratios*	*CI*	*p*
(Intercept)	0.05	0.00 – 1518.38	0.573	0.01	0.00 – 348.37	0.389	0.35	0.07 – 1.67	0.197	0.47	0.09 – 2.16	0.337
Age at depopulation (days)	1.01	0.99 – 1.03	0.574	1.01	0.99 – 1.03	0.410						
Duration of housing order (days)	1.00	0.99 – 1.01	0.747							1.00	0.99 – 1.01	0.990
Breed [B]	0.49	0.15 – 1.51	0.218	0.49	0.15 – 1.53	0.226	0.42	0.12 – 1.35	0.153	0.39	0.11 – 1.26	0.126
Breed [Other]	17979008.68	0.00 – NA	0.990	15846758.20	0.00 – NA	0.990	20262194.07	0.00 – NA	0.989	22056385.42	0.00 – NA	0.990
Housing system [Multi-tier]	1.67	0.58 – 4.93	0.343	1.58	0.54 – 4.74	0.404	1.59	0.50 – 5.16	0.428	1.62	0.52 – 5.19	0.408
Production system [Organic]	1.36	0.39 – 4.76	0.628	1.17	0.32 – 4.24	0.804	1.48	0.39 – 5.87	0.565	1.68	0.45 – 6.51	0.439
Season of placement [Winter]	1.56	0.56 – 4.44	0.396	1.44	0.51 – 4.14	0.495	1.27	0.42 – 3.87	0.675	1.40	0.47 – 4.21	0.547
Season of depopulation [Winter]	0.76	0.27 – 2.07	0.593	0.71	0.25 – 1.96	0.507	0.80	0.27 – 2.30	0.673	0.88	0.31 – 2.49	0.811
Housing order imposed [Yes]				2.19	0.82 – 5.97	0.119	2.04	0.71 – 6.02	0.187			
Age at depopulation (days) [512-518d]							3.75	0.73 – 22.22	0.123	4.41	0.89 – 25.92	0.080
Age at depopulation (days) [519-525d]							3.81	0.66 – 25.87	0.146	3.17	0.57 – 20.67	0.199
Age at depopulation (days) [526-534d]							2.17	0.40 – 13.01	0.376	2.03	0.38 – 11.89	0.411
Age at depopulation (days) [535-562d]							3.72	0.71 – 23.43	0.136	3.32	0.65 – 20.22	0.165
Observations	80			80			80			80		
R^2 Tjur	0.092			0.120			0.151			0.132		
AICc	122.582			120.220			125.429			127.196		

5.4 Discussion

5.4.1 Efficiency and scale

The analysis shows diversity in the sample in terms of flock size, production outputs, use of feed and energy resources, antimicrobial use, and feather scores. The relative efficiency scores suggest high levels of relative efficiency in this sample, with a mean score of 0.955 (minimum: 0.7211; maximum: 1.000) and a majority of 81% (65/80) of flocks attaining scores equal to or greater than 0.9. The majority of farms (94%; 16/17) produced at least one flock identified as relatively efficient. The high percentage of relatively efficient flocks is likely to be a function of the homogeneity in flock types and production systems within the sample. The observation that all but one farm produced at least one relatively efficient flock suggests that factors supporting relative efficiency are more likely to be flock-related than farm-related, and suggests that most of the farms are able to produce such flocks given the right combination of conditions. Further research is warranted to establish the possible differences in management between flocks on the same farms.

There were 29 flocks operating at an optimal size for transforming the selection of inputs into outputs, with a mean optimal flock size of 9,203. This result is applicable to the laying hen farms in this study and could inform processor policy regarding bird placement. Comparing these to the ‘large’ flocks, results suggest that an increase of around 2,000 birds from the optimal number placed could begin to compromise efficiency. Similarly, the ‘small’ flocks facing increasing returns to scale have not yet reached their optimal sizes, and may need to increase bird numbers by on average 2,000 to gain relative efficiency (Huguenin, 2012). Considering the components of the relative efficiency score, statistical analysis beyond the calculation of confidence intervals is not appropriate. However, the results in Table C (Supplementary Materials) and Figure 11 indicate that relatively efficient flocks had a slightly higher mean flock size at placement (9,340; 95% CI = 7,780-10,900) compared to relatively inefficient flocks (8,740; 95% CI = 7,480-10,000) but with overlapping confidence intervals. This is consistent with the benefits of economies of scale, such as the efficiency of energy use in larger flocks sharing a single house.

5.4.2 Performance of input and output criteria

By definition, the relative efficiency scores generated by DEA reward favourable performance against the input and output variables, and Tables C and D (Supplementary Materials) confirm that the flocks scoring the maximum relative efficiency score of one demonstrate superior performance compared to their peers on average across the majority of composite productivity measures. Looking at the average performance of each composite input and output variable and their derivatives for relatively efficient and inefficient flocks, it is not appropriate to apply statistics beyond confidence intervals. However, the variables of average number of eggs per hen day, estimated egg sales income, mean bird weight at depopulation and total biomass of birds transported for slaughter (meat production) were all favourable or very similar for relatively efficient compared to inefficient flocks, but with overlapping confidence intervals. These results indicate that in assigning relative efficiency scores using DEA, high relative productivity can be attained whilst achieving broader sustainability objectives. Higher average weights of individual birds in the relatively efficient group may be a result of breed and age effects, and may also correlate with better health at the end of life: Saraiva *et al.* (2021) found that septicaemia, emaciation, and carcass condemnation were more common in lighter birds. Biomass of the flock is of economic importance considering the contribution of spent hens to food production, as a by-product of the egg industry.

The environmental measures of mean energy use and mean feed conversion efficiency were superior for relatively efficient flocks compared to inefficient flocks, with non-overlapping confidence intervals for mean feed conversion efficiency. One farm in the supply chain is utilising their own solar panels for energy supply (Farm I in Table 17; personal communication from the egg packing company), but the majority are dependent on fossil energy. Energy efficiency as a sustainability imperative represents a proxy for carbon emissions, and future projects could incorporate carbon footprint data into a DEA model for a more accurate estimate of climate impact and to reward those utilising renewable supply. The process of feed production, including growing, processing, and transporting feed crop ingredients like soy, accounts for the most substantial environmental impacts in livestock systems

including land-use change, deforestation, and biodiversity loss (Laca at al., 2021). The farms in this sample all utilise externally-sourced poultry feeds (personal communication from the egg packing company), and future projects could disaggregate feed use by type and source to provide a more accurate estimate of the environmental and social risks associated with ingredient production and land use.

For animal health and welfare measures, antibiotic use (mean percentage bird days medicated) and mean mortality were lower for relatively efficient than inefficient flocks, but with overlapping confidence intervals. Flocks with a final feather score of 0 (no/minimal feather loss) had the highest percentage identified as relatively efficient, compared to those with poorer feather scores, although confidence intervals were overlapping (Table D, Supplementary Materials). Antibiotic use is dependent on multiple factors, often an outcome of health and welfare challenges, husbandry practices, and veterinary prescribing behaviours (Coyne *et al.*, 2016; Redman-White *et al.*, 2023). The mean levels of antimicrobial use in the study sample for both relatively efficient and inefficient flocks achieved (i.e., were lower than) the UK industry target of 1% (RUMA, 2023; VMD, 2023b). When antibiotic use was explored by class, no antibiotics categorised by the EMA as Category B ('Restrict') such as fluoroquinolones, 3rd and 4th generation cephalosporins, and colistin (EMA, 2020) were utilised by any flocks in the sample during the study period, in alignment with Lion Code regulations and the RUMA Task Force Target of less than 0.05% bird days medicated for these classes (RUMA, 2021).

Overall and as expected, flocks with relative efficiency scores of one demonstrated superior mean performance across the majority of sustainability indicators (Tables C and D; Figures 11 and 12), in particular for mean feed conversion efficiency, mortality, and energy use. However, because DEA balances multiple criteria and reflects each DMU's individual strengths in comparison to its peers, individual metrics for some relatively efficient units may be less favourable, and in some cases represent extreme outliers. This can be seen in the graphs in Figure 11 and in Table D (Supplementary Materials), in which unfavourable levels of certain indicators such as egg production per hen day, mortality, and feather score are observed for some relatively efficient flocks. This is also illustrated in Figure 12, which shows high levels

of variation and a complex association between the indicators when plotted against relative efficiency score as a continuous variable. Using DEA, flocks across the performance spectrum for each variable can be identified as relatively ‘efficient’, and this may necessitate the establishment of minimum requirement thresholds within supply chain settings for certain measures, to penalise via efficiency scores the units that transgress acceptable limits.

5.4.3 Predictors of relative efficiency

A multivariate regression relating relative efficiency with farm and production factors found that housing type, organic certification, seasonality, flock age at depopulation, breed, and housing orders did not influence a flock’s attainment of maximum relative efficiency, at the significance level of $p<0.05$. However, as an explanatory variable in univariate analysis, laying hen breed was statistically significant at the level of $p<0.1$, with a higher proportion of flocks of breed A attaining the maximum efficiency score, compared to flocks of breed B. This lacking or low significance of association between the attainment of maximum relative efficiency and the farm factors is likely to be due to the homogeneity of the flocks in the sample, which all conformed to free-range or organic standards, and further requirements of the egg packing company. Notwithstanding the low significance, an association between breed and sustainability performance is consistent with research from other sectors, suggesting that breeds with balanced genetic merit across the productivity, animal health and welfare, and environmental spectrum will play an important role in food systems seeking to mitigate externalities of production (Hartcher and Lum, 2020; Brito *et al.*, 2021).

There was variation in relative efficiency scores of the flocks of between 0.7 and 1.0, indicating a potential path of improvement amongst farmers with similar production systems and standards, partially relating to breed and potentially owing to unmeasured human factors. The particularly superior performance of the most relatively efficient flocks compared to inefficient flocks in terms of feed conversion efficiency, and to a lesser extent mortality and energy use, align with the idea that breed and other unmeasured human factors are important influencers of

sustainability performance in this supply chain. However, owing to the level of association and modest sample size, further investigation is warranted.

It should be noted that the data pertained only to the productive stage of the laying hen flock life cycle, excluding the rearing phase, and incorporation of rearing-phase data may reveal further opportunities for driving improvements. Furthermore, the input and output set only captured a limited array of sustainability concerns, and this could be addressed using standardised frameworks, expert elicitation, or stakeholder consultation to incorporate additional sustainability criteria (include positive measures) such as on-farm biodiversity, carbon footprint, keel bone scores, and social factors. This would strengthen the sustainability score, impact the performance score of each unit, and modify conclusions regarding the farm and production factors associated with relative efficiency. Furthermore, sampling flocks for such a study from the wider UK laying hen population including the different production systems in use (i.e., free-range, organic, barn and caged colony) could be fruitful in identifying further production system and farm characteristics associated with the attainment of multiple sustainability outcomes.

5.4.4 Future applications of DEA

To attenuate possible over-simplification of complex sustainability challenges using single scores (Grandin, 2022), individual criteria must be scrutinised to ensure that regressive trends and trajectories in individual indicators are addressed. In commercial supply chains, it may be necessary to establish ‘red line’ thresholds to various metrics, and when these acceptable limits are transgressed by a DMU, their efficiency score could be downgraded. A general limitation of DEA is the need for reliable and often hard-to-reach datasets relating to multiple indicators monitored over the lifecycle of several comparable farm units. Deploying DEA as part of a supply chain approach or government policy would therefore be contingent upon robust data collection systems and agreements, and motivated participating producers and processors who mutually benefit from collecting and sharing their data with downstream supply chain actors. Hardware systems including but not limited to the BirdBox system used in this study could periodically run automated

DEA and regression analyses on assimilated datasets with a user-friendly farmer interface and linked farmer incentive scheme, to routinely benchmark flocks, reward relative best performers, and inform supply chain policy for continuous improvement.

5.5 Conclusions

The use of DEA expands the basic two-dimensional definition of efficiency, and reframes it as a multi-criteria relative valuation that can include multiple sustainability metrics. These measures can represent frequently neglected concerns such as animal welfare and antibiotic use. A large proportion of flocks in this sample attained the maximum relative efficiency score, indicating good performance amongst the free-range flocks but also reflecting the similarities between them. Presenting the performance of flocks in terms of the individual composite criteria, we confirm the favourable performance of relatively efficient flocks across a broad array of criteria, concluding that some farms in this sample are successfully reconciling superior environmental, animal welfare, and antibiotic use performance with production goals.

Exploring the farm and production factors associated with the attainment of maximum relative efficiency, we demonstrate how DEA scores can be leveraged to inform actionable changes and supply chain policy, for example relating to production and housing systems, breed, and husbandry decisions. No statistically significant associations at the level of $p<0.05$ were identified between farm and production factors and the attainment of efficiency, indicating that no flocks were at an advantage or disadvantage in attaining maximum relative efficiency based on the input and output criteria set selected. However, univariate analysis revealed an association between laying hen breed and the attainment of relative efficiency at the level of $p<0.1$, agreeing with other authors asserting that breeds with balanced genetic merit will play an important role in food systems seeking to mitigate externalities of production. As well as proposing further research into this association with a larger and more diverse sample of flocks, we conclude that considerable gains can still be made amongst farmers working with similar production systems and

standards, likely owing to both breed and unmeasured influences such as human factors.

There are many additional opportunities for the application of DEA to support agricultural sustainability. Sustainability criteria could be selected utilising standardised frameworks, expert elicitation, or stakeholder consultation, to comprehensively include and account for all known externalities, e.g., carbon footprint and biodiversity loss. Furthermore, the outputs could move beyond the negative impacts and production metrics used in this study to include *positive* sustainability criteria that are increasingly valued and measured (Edgar *et al.*, 2013; Jordon *et al.*, 2022), such as indicators of positive animal welfare, soil organic carbon, biodiversity scores, and social wellbeing, the inclusion of which will modify and strengthen conclusions regarding the farm characteristics and production systems associated with relative efficiency. DEA could be applied to DMUs representing any agricultural production system, including those deploying sustainable intensification or agroecological approaches. Regular DEA benchmarking of the same group of producers against their peers could foster continuous improvement and represent a practical means of incentivising best practice within supply chains or government schemes.

CRediT authorship contribution statement

Laura Higham: Conceptualisation, Investigation, Data Curation, Formal analysis, Visualisation, Writing - Original Draft, Project administration. Ian Handel: Data Curation, Formal analysis, Visualisation, Writing - Review and Editing. Lisa Boden: Conceptualisation, Methodology, Writing - Review and Editing, Supervision. Dominic Moran: Conceptualisation, Methodology, Writing - Review and Editing, Funding acquisition, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Laura Higham reports a relationship with the anonymous egg packing company providing the data for this study that includes: consulting or advisory. The egg packing company that kindly provided the raw data for this project is a consultancy and hardware client of FAI

Farms, for which the corresponding author works as a consultant. However, the egg packing company, which remains anonymous in accordance with a data sharing agreement, did not influence the results or interpretation of this study. Their provision of data and contextualising information (noted as personal communications in this manuscript) are acknowledged. The other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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5.6 Next steps

This chapter demonstrates the use of multi-criteria decision-making to benchmark farming units and inform best practice. Responding to research question 4, this tool represents a practical methodology that could be deployed by veterinary, agricultural, and government stakeholders to support the inclusion of animal welfare and antimicrobial stewardship considerations into sustainability decision-making. However, as discussed in the section 5.4.4, this method is contingent upon robust data collection systems and equitable agreements between supply chain actors. This represents an important role for veterinary professionals, producers, processors, and retailers to broker such agreements and implement robust data collection.

Furthermore, the criteria set on which to base such evaluations is often poorly defined and misunderstood. In the next chapter, we move from the production to the consumption-side of the food chain, to explore the desirable food system outcomes

required by a community. We compare these outcomes to those associated with the emerging ‘regenerative agriculture’ concept, and respond to research questions 3 and 4 by assessing the barriers to delivery of the desirable food system outcomes and proposing a blueprint for driving sustainability performance within a public procurement setting.

6. Regenerative food futures: One Health approaches to public food procurement at a UK university

Regenerative agriculture (RA) is considered to represent an ancient approach to food production, premised upon the renewal of resources and inspired by natural ecosystems. However, the term is contested due to its lack of a commonly-agreed definition. We explore different ways in which RA is framed, and how its principles may support food procurement policies that enable public institutions to deliver local and global sustainability outcomes. This chapter identifies the actions that could be taken by public policy makers to support a sustainability agenda that incorporates human, animal, and environmental considerations.

A manuscript version of this chapter is currently under peer review with *Agroecology and Sustainable Food Systems* journal.

6.1 Introduction

Several sustainability challenges are presenting existential threats to humanity and Earth's ecosystems. Six of the nine notional planetary boundaries defining the safe operating space for humanity have been transgressed (Richardson *et al.*, 2023), and health and social disparities are increasing (Cascio *et al.*, 2011; Collignon *et al.*, 2018; Chancel *et al.*, 2022). Agriculture occupies the largest percentage of habitable land on Earth (Richie and Roser, 2019) and is central to the sustainability agenda. Indeed, the rise of large-scale, intensive farming has supported significant increases in food supply to a growing human population with increasing resource use efficiency (Manshanden *et al.*, 2023). However, the generation of harmful externalities such as greenhouse gas emissions (Richie and Roser, 2020), soil degradation (Tsiafouli *et al.*, 2015), biodiversity loss (Benton *et al.*, 2021), mental health problems (Parrón *et al.*, 1996) and poor animal welfare (McInerney, 2004) are motivating interest in alternative food systems, such as regenerative agriculture.

Regenerative agriculture (RA) is a loosely-defined concept (Newton *et al.*, 2020); but it broadly reflects an ancient philosophy of working *with* nature to produce food, whilst revitalising ecosystems and communities (Hes and Rose, 2019; Schreefel *et al.*, 2020; O'Donoghue *et al.*, 2022). Its core principle appears to be moving 'beyond' sustainability, which implies maintenance of a degraded baseline, towards renewing and enhancing natural, human, and social capital (Reed, 2007; Schreefel *et al.*, 2020). In contrast to certified agroecological niches such as 'organic' (UK Government, 2023a), 'biodynamic' (Demeter: Biodynamic Federation, 2023), and 'Pasture for Life' (Pasture for Life, 2024), regenerative farming is being adopted and marketed by a grass-roots movement of self-identifying producers in the absence of regulation or a widely-adopted standard. Founded on indigenous wisdom (Dahlberg, 1994) and championed since the 1970s (Gabel, 1979; Rodale, 1983), its advocates include practitioners, researchers, and citizens, as well as several large food corporations that are attempting to embed its principles into their sourcing commitments (Unilever, 2021; General Mills, 2023; PepsiCo, 2023). However, against a backdrop of statutory procurement frameworks, profit motives, and competing agricultural niches, the RA movement has gained limited traction within the UK public sector to date.

Representing an annual spend of £2 billion per year (Environment, Food and Rural Affairs (EFRA) Committee, 2021), public food procurement (PFP) is a substantial lever for the government to lead a food agenda towards sustainable production and healthy diets in a range of settings, including schools, universities, hospitals, care homes, prisons, and military canteens (Swensson and Tartanac, 2020). However, PFP has been criticised for its ineffective use of public budgets to drive food standards and support domestic producers (EFRA Committee, 2021). Although regulated agroecological systems such as organic have been successfully integrated into PFP in countries like Denmark (Organics International for organic farming organizations (IFOAM), 2020), such initiatives have not been widely adopted across the UK. The concept of RA, however, is attracting some interest in the context of public food policy and government strategies: recommendations in the UK's National Food Strategy Plan involve investing to create a better food system, including regenerative farming practices that *"work with nature instead of against it"*, and strengthening government PFP (Dimbleby, 2021). The Scottish Government

references a *"flourishing"* natural environment, *"improving"* animal welfare, and the *"regeneration"* of biodiversity in the six outcomes it seeks to deliver through its Good Food Nation Plan (Scottish Government, 2024). The UK's DEFRA has pledged its support of regenerative practices via its Agricultural Transition Plan and Environmental Land Management Scheme (DEFRA, 2020).

Furthermore, several university consortia are seeking transformations towards regenerative food systems, including for public settings (Ryland, 2020; Doherty *et al.*, 2022). Opportunities to integrate RA into PFP have been explored in a small number of studies. One study investigated pathways to an agroecological transition in university food procurement settings in Spain, citing high levels of understanding of food system impacts, demand for change amongst consumers, and the power of university networks to act as agents of social change (Cruz Maceín *et al*., 2023). Grech *et al.* (2020) concluded that sustainable food systems are considered in some university governance documents in Australia, but their focus on stand-alone waste management or fair-trade standards were likely to have minimal impact. Collaborations were fundamental to supporting healthy and sustainable diets on university campuses according to Franchini *et al.* (2023), who concluded that bringing together diverse expertise, skills, and experience could foster wellbeing amongst the university community.

The University of Edinburgh was the highest-ranking university in Europe for sustainability performance in 2023 (Quacquarelli Symonds Limited (QS), 2023), with academic expertise in sustainable food systems and significant purchasing power. We sought to derive a set of RA principles in this university context, and to determine if the application of these principles could enable PFP to deliver the outcomes considered desirable by informants from the University of Edinburgh community. We used thematic analysis (QSR International, 2023) of 20 semi-structured interviews with anonymous key informants from the University community and external organisations, enriched with verbatim quotes from key informants to illustrate key themes. In this article, we offer a set of desirable outcomes for university food, with wider relevance to the global food system, and map these against the University of Edinburgh's existing food policy. We then present a summary of key informant descriptions of RA, and identified barriers to attaining desirable food system

outcomes. We conclude by proposing a set of RA principles and initiatives to operationalise a future food system within a university landscape.

6.2 Methods

This study is based on interviews with 20 anonymous key informants from the University of Edinburgh's staff and student community, and external organisations. Prospective key informants were selected by purposive sampling to involve key stakeholder groups including students, subject area specialists, producers, and industry and NGO representatives, from the relevant disciplines of farming, food policy, global health, nutrition, food procurement and catering, social justice, environmental sciences, ecology, veterinary science, and animal welfare. They also fulfilled the criteria of: (1) being either a University of Edinburgh student (n=3) or staff member (n=8), producer/farmer (n=4), NGO representative (n=2), or industry representative (n=3); and (2) being available for interview during the month of May or June 2023. Of 23 individuals approached for interview via email, 20 provided their informed consent (equating to an 87% response rate) and participated in one-to-one semi-structured interviews of one-hour duration with the first author in May and June 2023. Key informants were invited to participate on a voluntary and anonymous basis, in order to encourage open and honest disclosure of insights and perspectives.

Nine interview questions (see Supplementary Materials) were shared with the key informants in advance, with all questions being optional and flexible, allowing topical lines of enquiry to be explored according to the direction of the discussion. Interviews conducted via Microsoft Teams were recorded and transcribed using the live transcription feature, and all transcriptions were cross-checked for accuracy against the original recordings and hand-written notes taken during interviews. Transcriptions were then subject to Thematic Analysis using qualitative analysis software NVivo14 (QSR International, 2023), following an iterative coding process to organise the interview responses into the sub-themes for each of the following sections: (1) desired outcomes of the global and university food systems; (2) barriers

to attaining these outcomes; (3) characteristics of RA; and (4) future university food. We followed a six-step process (Braun and Clarke, 2006) to analyse data with thematic analysis: (1) becoming familiar with the data, (2) generating initial codes, (3) searching for themes, (4) reviewing themes, (5) defining and naming themes, and (6) producing the report. Coding identified the different themes, before qualitative summaries of the data were generated (Tables 21, and 23-25). Analyses were conducted by the first author, with themes and sub-themes ratified by the second author.

This research received ethical approval from the HERC at the Royal (Dick) School of Veterinary Studies in May 2023, under application number HERC_2023_070.

6.3 Results

6.3.1 Required outcomes of university food

Key informants proposed multiple desirable outcomes for the global and University of Edinburgh food systems. Themes of the responses (Table 21) reflect a collective view that food systems must deliver multiple outcomes across the human, animal, and environmental (also known as 'One Health' (OHHLEP, 2020)) domains:

> *"I think in one word, the outcome of the global food system should be health - that is human, animal, plant, soil and planetary health."*
>
> - Producer interviewee

> *"I suppose the first and foremost [goal of our global food system] is to provide sufficient food for our nutritional needs…we have to do that while maintaining or improving our natural capital and our social capital…As part of that, what do we do today, we need to do better on animal welfare…I feel it comes as an afterthought to most people working in the sustainability space."*
>
> – Staff interviewee

The outcomes required of the global food system were reflected in the desired outcomes of university food. However, some informants emphasised the particular importance to university students of affordable food, nutrition for mental health,

fostering social cohesion though food, and sourcing to reflect the sustainability concerns of students. For example:

> *"You [the University] have got to make sure that the price of the food that you're selling is reasonable, because people are students and they've not got a lot of money. But you've got to make sure that it's not a sort of market failure in the sense that someone's losing out along the supply chain because they're not being paid properly for their services or the environment - it's not being taken into account properly."*
>
> – Student interviewee

Additional themes of food education and leadership were also specified for universities, pointing to opportunities to support the future food habits of graduates and leveraging academic expertise and leadership through procurement and catering:

> *"[The challenge is] how we make sure that the 10,000 graduates that we have every year make a real change in the world that they go into, so that they have a better understanding of how to eat sustainably, what good food looks like on a personal level, as well as on whatever career path they decide to go on."*
>
> – Staff interviewee

In the process of expressing these outcomes, key informants raised their concerns regarding the externalised costs of the existing global food system, to ecosystems, social justice, and animal welfare, in the pursuit of resource use efficiencies and cheap food. To understand the extent to which the set of desirable food system outcomes are currently fulfilled at the University of Edinburgh, the outcomes were mapped against the University's food commitments and policies available in the public domain (Table 22).

6.3.2 Informant descriptions of regenerative agriculture

Informant descriptions of RA were categorised into themes (Table 23). General characteristics included moving beyond harm reduction to improvement and regeneration; being inspired by the dynamics and richness of natural ecosystems, of which humans are a part; and drawing from traditional and indigenous wisdom:

"I think that's another fundamental shift we need to make is - at the moment, we're very focused on reducing our emissions, trying to get to net zero. Those things are all about doing less harm. We've already done a lot of harm and we need to start doing good. We've got to move beyond sustainability. You know we can't sustain the status quo because that's not good enough."

– Producer interviewee

"Regenerative agriculture is an approach to agriculture that not only looks to mitigate harm done, but actively works to reverse existing damages and to have beneficial outputs in terms of environmental impact…like soil health and biodiversity, and animal welfare. It evokes a sense of…return[ing] to our foundations and our origins…when people just lived as part of the world rather than looking down on it."

– Staff interviewee

"So for me, the fundamental thing is about a shift of values in terms of how we think about ourselves in nature and the welfare of animals, and also the importance of actually nourishing people, not just making money."

– External stakeholder/producer interviewee

Some informants explained the deep relationship between regenerative practitioners and land and nature, often provoked by a mindset transition:

"I see people in regenerative agriculture as, very often, having woken up to something, and they're really very courageously exploring this new terrain."

– Staff interviewee

"When you speak to farmers who've gone through this transition, you never meet a farmer who comes out of it, who hasn't become more connected to and passionate about what they do…they are much more connected to the land…and their animals and the wider biodiversity. I visited a farm…he was a pretty large mixed arable and beef [farm]. But he also has been involved for about 10 or 15 years in supporting really rare birds…I came out of it going - this man now values his birds in the same way that he values his cows. They're now part of his farm."

– Staff interviewee

Table 21: A summary of the proposed outcomes of global and University food systems according to 20 key informants.

Food system outcomes		
HUMAN	1	**To provide nutritious, appetising, and diverse food choices for physical and mental health**
		Nutrition for physical health and development
		Tasty food with variety
		Accommodate dietary needs and preferences
		Nutrition for mental health
	2	**To ensure affordable and accessible food for all**
		Equitable access and availability
		Affordable food
	3	**To supply sufficient, safe food for all**
		Supply sufficient food
		Supply safe food
	4	**To create safe, fair, and decent livelihoods in food and farming, and thriving local communities**
	5	**To celebrate diverse food cultures and build social cohesion**
ANIMAL	6	**To ensure that all animals in food systems experience a good life, by upholding high standards of animal welfare**
ENVIRONMENT	7	**To conserve and regenerate natural resources**
	8	**To protect and enhance biodiversity**
	9	**To minimise and recycle waste to create a circular food system**
	10	**To build soil health**
	11	**To support clean air and water systems**
	12	**To mitigate greenhouse gas emissions and achieve net zero**
Outcomes specific to universities	13	**To embed food education at the University**
	14	**To demonstrate sustainable food systems leadership, in principles and practice**
		Showcase the University as a beacon of civic responsibility and leadership
		Apply food systems research and innovation

Table 22: Existing certification schemes, standards, and awards upheld in food procurement at the University of Edinburgh, and their relevance to the proposed food system objectives in Table 21. Cells shaded in dark grey signify schemes or standards that explicitly reference *an aspect of* the objective.

Certifications, award schemes, and policies	PROPOSED FOOD SYSTEM OUTCOMES														COMMENTS
	To provide nutritious, appetising & diverse food choices for physical & mental health	*To ensure affordable & accessible food for all*	*To supply sufficient, safe food for all*	*To create fair, safe, & decent livelihoods in food/farming, & thriving local communities*	*To celebrate diverse food cultures & build social cohesion*	*To ensure that all animals in food systems experience a good life…*	*To conserve & regenerate natural resources*	*To protect & enhance biodiversity*	*To minimise & recycle waste to create a circular food system*	*To build soil health*	*To support clean air & water systems*	*To mitigate greenhouse gas emissions & achieve net zero*	*To embed food education at the University*	*To demonstrate sustainable food system leadership…*	
Red Tractor assured meat (Red Tractor Assurance, 2023)			■	■		■			■		■				Basic standards, including for animal welfare.
Marine Conservation Society-rated fish (score 1-3) (MCS, n.d.)							■	■							No wild fishery / aquaculture standards.
Good Egg award (Compassion In World Farming, 2023)						■									Covers cage-free shell eggs; excludes ingredient egg.
Food For Life Bronze Award (Soil Asso'n, 2018)	■		■	■	■	■	■	■	■		■		■		In catered halls only.
Fair Trade Policy (University of Edinburgh, 2020a)				■											Focuses on securing rights of producers and workers.
Sustainable Restaurant Association 'Food Made Good' 3 stars (SRA, 2023)	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	Standard not available in the public domain.
Food For The Brain Award (Food for the Brain Foundation, 2023)	■														Focus on mental wellbeing and brain health.
Peas Please Rising Star Award (The Food Foundation, no date)	■	■										■			Campaign to increase vegetable consumption.
University sourcing policies (Good Food Policy *etc*) (University of Edinburgh, 2020b)	■	■	■	■	■	■	■	■	■		■	■	■	■	Include policies on Fair Trade, Palm Oil, Good Food *etc.* Carbon footprint data is available online for meals in cafes and catered halls.

KEY: ■ Contains relevant standard No relevant standard ▒ Standard unknown

Others asserted the importance of regeneration as a set of *outcomes*, which are used to inform the application of context-specific practices:

> *"We must be clear that this is about regenerative outcomes, not regenerative practices, because people get very hung up on 'Oh well, I'm doing all these regenerative practices', but they don't necessarily lead to regeneration and unless they're being done in the right way, and on each farm it will be different."*
>
> – Producer interviewee

Table 23: Characteristics of 'regenerative agriculture', categorised into general characteristics, outcomes and processes based on thematic analysis of transcripts from 20 key informants from the University of Edinburgh community.

Characteristics of regenerative agriculture
General characteristics
Beyond 'sustainable', to restoration and improvement
A part of, and inspired by nature
Traditional, indigenous agriculture
Whole farm, systems approach
Deep relationship between the farmer and the land
Mindset transition
Outcomes-driven
Practices
No or low use of synthetic inputs; e.g., fertilisers, herbicides, or pesticides
Increasing agrobiodiversity; e.g.; poly-culture; integrated multi-trophic aquaculture
Limiting soil disturbance through no or low use of tillage
Covering the soil; e.g., with living plant cover, perennials, and long swards
Integration of farmed animals; adaptive multi-paddock grazing
Integrating trees; e.g., agroforestry and silvopasture
Outcomes
Improve soil health
Production of abundant, nourishing food
Increase biodiversity
Provide rewarding livelihoods and support local communities to thrive
Positive animal welfare
Carbon sequestration
Human health and wellbeing
Improve water resources (quality and availability)

However, key informants collectively characterised RA in terms of *both* practices and outcomes. For example, the practice of increasing the number of species on farm (agrobiodiversity) *and* the outcome of improving biodiversity emerged in the context of polyculture or multi-trophic aquaculture and agriculture:

> *"From an aquaculture perspective, what we're doing is integrated multi-trophic aquaculture. So trying to have various trophic species, all growing together, so you get that kind of symbiotic relationship."*
>
> - Producer interviewee

The themes in Table 23 suggest that RA is understood to be rooted in a set of common *values*, led by *outcomes*, and enacted through context-specific *practices* (Figure 13).

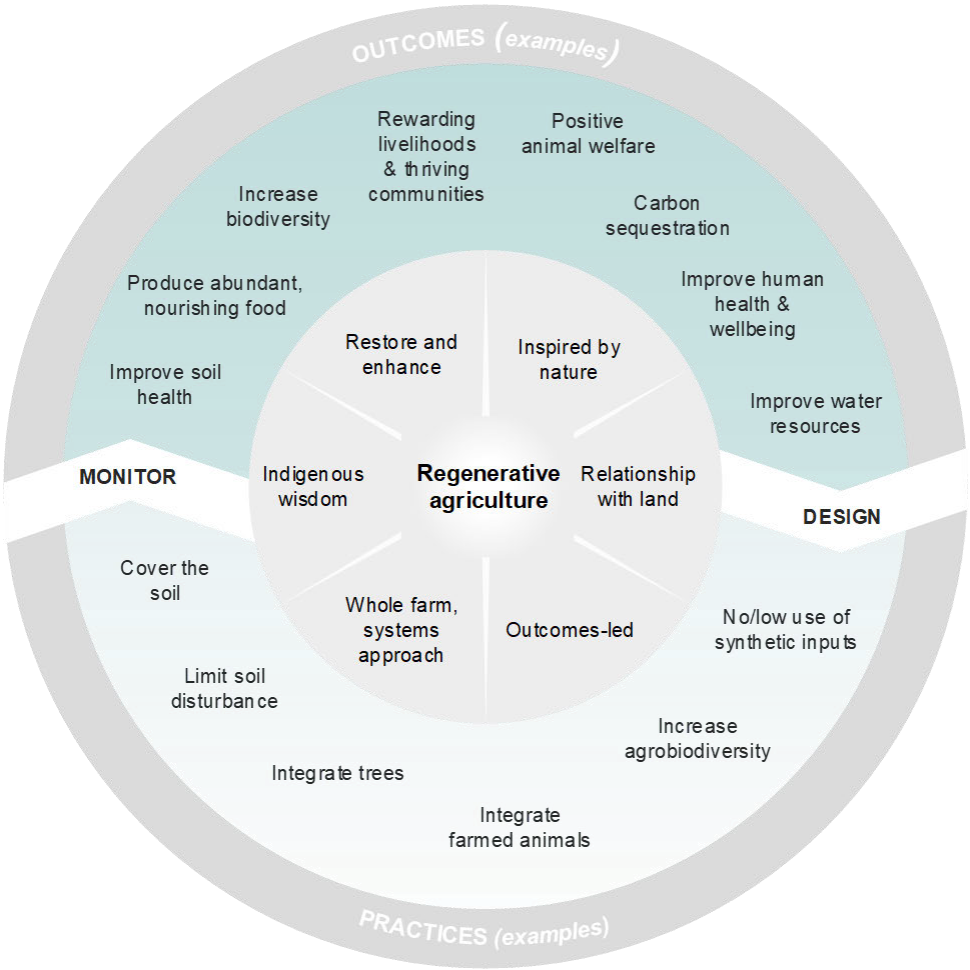

Figure 13: Characteristics of 'regenerative agriculture', categorised into common values (central circle), outcomes, and practices, based on thematic analysis of transcripts from 20 key informants from the University of Edinburgh community.

Informants also acknowledged the absence of a commonly-agreed definition of RA, enabling farmers to establish their own objectives and context-specific practices:

> *"One of the things I'm excited about 'regen ag' is that it's bottom up. It might well have a whole load of solutions to the social factor, because it's not me telling you…There might be some really fundamental, exciting things coming from movements which can work with what people are interested in."*
>
> Staff interviewee

Limitations and uncertainties were also captured regarding the lack of a commonly-agreed definition and regulation around RA, and the subsequent vulnerability of the term to greenwashing by corporations. Informants also expressed a discordance in viewpoints on the land sharing-land sparing continuum (Fraanje, 2018), and the perceived low land use efficiency of RA; the necessity for accompanying diet changes based on what farms can provide; and the use of farmed animals as 'tools', with potential welfare implications:

> *"Regenerative agriculture should be about regenerating the soil biome…but for me, it's undefined, it's not regulated and it's really, at this point in time, little more than a marketing tool."*
>
> – Producer interviewee

> *"You can find in some circumstances that within the EOV [Ecological Outcome Verification] that animals are tools for land restoration. And sometimes people come to that from that angle only and there may be welfare implications."*
>
> – Producer interviewee

6.3.3 Barriers

Key informants identified several barriers to attaining the proposed outcomes (Table 24), with some relating to both university environments and wider society. These included barriers around the design and delivery of standards, including inequitable access for farmers to markets, standards that do not necessarily drive positive outcomes, and the failure of standards to accommodate each unique farming context. Policy incoherence was referenced in relation to PFP.

"[X] British logo and you see it quite often. It means next to nothing. I mean the standards are only barely above the legal minimum and yet…I think a lot of people would think that if they're buying that, that it's guaranteeing some form of welfare, which it really isn't. I mean…the animals that are living in [X assurance scheme] systems are suffering a lot on a daily basis."

- External stakeholder interviewee

"The problem with certifications or frameworks is that they're often very prescriptive. What's right for this farm and its topography and reversing the damage that has been done to it is totally different from my neighbour's farm, only metres away."

– Producer interviewee

"The public sector [are] saying to the farmers: Well, we want you to deliver public goods but we're not even going to buy it, [instead we'll] buy the stuff, you know, that's cheapest."

– Producer interviewee

Barriers cited by informants also included human factors such as poor citizen understanding of food production standards and provenance, and a lack of consensus on sustainable food systems, as well as financial constraints around buying and preparing food. Some students identified their lack of cooking skills as a specific constraint.

"There are many – too many [certification schemes] – and it becomes confusing for consumers because they don't carry the same weight or credibility. On the surface, seeing a product with a certification evokes a feeling of trust in the quality, sustainability, ethics etc. of the product, but this can be misplaced trust. The onus is on the consumer to either accept these at face value, or do their research to understand what these certifications and frameworks actually mean."

– Student interviewee

"It is difficult…because the researchers at the University are often on both sides of the debate. So we have researchers…who are trying to make animals more productive so that we can continue to farm them in the same way that we always have. Whereas actually there's other the other side of the coin saying, well, actually no. We need to be removing animals completely from our food systems or heavily reducing them."

– Staff interviewee

"We've sort of started eating vegetarian and realised I'm not getting [a balanced diet] because I don't know very many good vegetarian recipes…from that I've expanded and I'm starting to eat healthy again, but it can take time and research as well."

– Student interviewee

Table 24: Barriers to attaining food system outcomes, categorised based on thematic analysis of transcripts from 20 key informants from the University of Edinburgh community.

	Barriers to attaining outcomes
	Governance
1	Design and delivery of standards
	Standards create inequitable access to markets
	Standards do not necessarily drive positive outcomes
	Standards do not accommodate the farming context
2	Policy weakness and incoherence
3	The rise of ultra-processed and unhealthy foods
4	Perverse incentives (e.g., production subsidies)
	Human factors
5	Citizen understanding of food production standards and provenance
6	Dietary norms
7	Lack of consensus on sustainable food systems
	Discordant opinion on food system goals
	Discordant opinion on delivery of a sustainable food system
8	Farming norms
9	Fragmented knowledge and skills in nutrition and food preparation
10	Fragmented knowledge and skills in food production and processing
	Financial
11	Costs of buying and preparing food, and competing household priorities
12	High production costs and low food prices
13	Lack of finance for capital investments
	Social inequities
14	Power asymmetry in supply chains
15	Inequitable access to healthy food (including food deserts on campus)

6.3.4 Future university food

Initiatives for a future university food system were categorised into themes (Table 25). Integrating teaching and learning into food procurement and the supply chain through direct farm partnerships and into the university curriculum were expressed by some key informants:

> *"The way to do it would be to reduce reliance over time [on catering wholesalers] and maybe the chefs in the kitchens are able to produce one meal a week that they do from scratch and that have some direct relationships with where that food is coming from. Transitioning those farmers and then having an off-take agreement with them that you took whatever they could grow, and it's likely that would change overtime as they might introduce trees, they might introduce other livestock, they might start growing vegetables."*
>
> – Producer interviewee

> *"We can just make sure most of our own student body understand where their food is coming from and how we embed that into a sustainable curriculum."*
>
> *– Student interviewee*

These initiatives were validated against the food system objectives in Table 21 and barriers in Table 24, and all objectives and barriers were addressed by the proposed initiatives.

Table 25: Initiatives proposed for a future university food system, categorised based on thematic analysis of transcripts from 20 key informants from the University of Edinburgh community.

Future food at the University of Edinburgh	
A.	**Core programme**
1	*Multi-stakeholder participation / stakeholder assemblies*
2	*Cohesive, ambitious sustainability strategy*
3	*Collaborations across the public sector*
B.	**Farm partnerships**
4	*Provision of on-farm research, innovation, and learning opportunities*
5	*Partner with and provide a reliable direct market for local producers*
C.	**University food standards**
6	*Implement adaptive menu-setting*
7	*Standards to reflect University values*
8	*A circular economy for food, waste, and packaging*
9	*Clear communication of standards and provenance*
D.	**Social value**
10	*Provision of food and sustainability education*
11	*Growing food on University land*
12	*Not-for-profit University food*
13	*Building community with food (social and cultural occasions)*

6.4 Discussion

6.4.1 What outcomes are required by the University community?

The set of proposed food system outcomes span the One Health domains, including but not limited to equitable access to nutritious, safe, and affordable food, fair livelihoods in food and farming, a good life for all animals in our food system, and the conservation and regeneration of natural resources. The outcomes of affordability, mental health, social cohesion, food system leadership, and education were additionally proposed for university food environments, to leverage their vital role and influence in the lives of students and graduates.

Mapping the desirable outcomes against the existing food policies and commitments published by the University of Edinburgh, Table 22 indicates that the schemes collectively have to potential to cover all objectives except for ‘building soil health’.

However, some of the assurance schemes on which University standards are based were considered by some key informants to inadequately support animal welfare and environmental stewardship. Higher tier assurance schemes (RSPCA Assured, 2023) and augmented University policies could deliver the desirable food system outcomes by, for example, promoting positive behaviours and “good life” experiences (Mellor, 2016) for farmed animals in its supply chain, and prohibiting long-distance transport, routine prophylactic antibiotic use, use of harmful herbicides and pesticides, and the sourcing of forest risk commodities. Although commendable for enacting a suite of sustainable food initiatives, the University’s policies reflect the economic and bureaucratic constraints within UK public food procurement. By applying higher standards and fostering student-led farming initiatives, some universities in the UK and across the world have demonstrated how certain facets of public food policy can be bolstered (Cornell University, no date; Compassion in World Farming, 2015; University of Greenwich, 2024).

6.4.2 How was regenerative agriculture described by the key informants?

RA was characterised as being rooted in a set of common values, led by outcomes, and enacted through context-specific practices. Key informant descriptions of these characteristics were well-aligned with the wider literature. ‘Regeneration’ - the process of rebuilding resources (O’Donoghue *et al.*, 2022) - has been enacted in a variety of disciplines, locations, and cultures for centuries (e.g., Attia, 2018; Hart, 2008; Joffre *et al.*, 1999; Sampogna *et al.*, 2015), but has attracted growing attention since the late 1970s in opposition to high input-high output, tillage-dependent farming systems (Gabel, 1979; Rodale, 1983). Echoed by key informants, scholars point to the limitations of the term ‘sustainability’, and the need to work towards restoration and enhancement of resources (Brown, 2018; Morseletto, 2020).

Some authors suggest that restructuring and decolonising ‘industrial’ agriculture is necessary, by rekindling traditional food systems (Dahlberg, 1994) and indigenous land custodianship (Hes and Rose, 2019), in which regenerative values are rooted. An ontological shift amongst RA practitioners from anthropocentric perspectives on resource use, towards an ecological mindset that respects the intrinsic value of nature and non-human species (Reed, 2007; Hofstra and Huisingh, 2014) was

captured during interviews. Some described a mindset shift in producers towards viewing their farms as part of - but not central to - the wider ecosystem, with additional positive impacts on their own wellbeing. Gosnell and others (2019) similarly found that health and happiness, low stress, humility, integrity, and nature stewardship were motivating factors for regenerative practitioners. Gregory (2022) discovered an improvement in mental health amongst farmers using RA, attributing this to a *'return to humanity's ancient biophilic relationship with nature'*. An increase in production and/or profit within regenerative systems relating to reduced input costs was described by during key informant interviews – a finding supported by others (LaCanne and Lundgren, 2018).

The results suggested RA discourses are emergent and diverse, resulting in a lack of legal, regulatory, or commonly-accepted definitions for the term. Although regenerative standards exist, they are currently niche in the UK (e.g., A Greener World, no date.; Regenerative Organic Alliance, 2023; Savory Institute, no date), and some informants remarked that the absence of a commonly-accepted definition or standard was of benefit to producers, enabling them to shape their practices according to the unique context of the farm. However, the void can also engender a lack of clarity for citizens, researchers, and policy makers, and can stifle research and government investment (Newton *et al.*, 2020). Several informants highlighted the vulnerability of the concept to greenwashing by private interests, which can diminish and corrupt the wider movement.

The lack of common definition also casts doubt on the criteria to be 'regenerated'. Although the proposed outcomes of RA (Table 23) included regeneration across the One Health domains, the *environment* is the focus for many scholars. One review concluded that *"the soil is the base"* of RA, reporting a convergence in definitions around enhancing the environment and supporting the socio-economic dimensions of food security (Schreefel *et al.*, 2020). Animal welfare is often considered to be an implicit benefit of extensive systems that enhance wider ecosystem functioning (Hargreaves-Méndez and Hötzel, 2023), yet key informant interviews captured concerns that failure to *explicitly* include welfare and other neglected domains into RA could generate harmful trade-offs. Indeed, the narrative of farmed animals being

used as ‘tools’ within RA or rewilding settings risks perpetuating the commodification of farmed animals in pursuit of other goals (Hargreaves-Méndez and Hötzel, 2023).

In the absence of a definition, a variety of interpretations of RA have emerged in the literature, including those that define it based on a set of common *practices*, a set of *outcomes*, and a blend of both (Newton *et al.*, 2020). Indeed, both practices and outcomes were included as characteristics of RA by key informants. Although practice-based agricultural niches are common-place within the existing food system, with established means of regulating and certifying produce, such systems were criticised by informants for creating inequitable access to higher-value markets, not necessarily driving positive outcomes, and failing to accommodate each unique farming context. Furthermore, trade-offs may arise when practices are prioritised over outcomes: reports suggest that some farmers may increase their herbicide use to tackle weed growth in their transition to ‘no till’ (Pullman, 2023). Outcome-based agricultural niches, in contrast, may enable producers to make decisions based on their own context guided by principles and objectives, but are more complicated to define, regulate, certify, and reward, based on conventional rule-based policy and marketing instruments, such as food standards and labels.

However, the inclusion of both outcome *and* practice-based characteristics of RA are justified by some by a strong theory of change that the specified practices can indeed generate the desired outcomes (Newton *et al.*, 2020). Integrated multi-trophic aquaculture (IMTA) systems, and their terrestrial polyculture equivalents such as agroforestry, food forests, silvopasture, and permaculture, were referenced by informants as examples of such processes with proven outcomes in many contexts. For example, some aquaculture practitioners are forging a model of polyculture (Khanjani *et al.*, 2022) that can attain regenerative outcomes through the simultaneous cultivation of, for example, seaweeds, bi-valves, and finfish, and additionally bridging the divide between intensive and extensive systems.

6.4.3 Can regenerative agriculture enable public food procurement to deliver the proposed outcomes for the University community?

Notwithstanding its limitations, the RA outcomes displayed in Table 23 and Figure 13 align closely with the desirable food system outcomes in Table 21, particularly for the supply-side outcomes related to soil health, food production, farming livelihoods, biodiversity, animal welfare, carbon sequestration, and water resources. The desirable outcomes and RA outcomes also mirror the One Health concept, defined as "*an integrated, unifying approach that aims to sustainably balance and optimise the health of people, animals, and ecosystems*" (OHHLEP, 2020). Furthermore, RA's core value of restoring and enhancing ecosystems and communities supports, in principle, the University of Edinburgh's Strategy 2030 to '*make the world a better place*' (Sked, 2021). This suggests that a framework inspired by RA values, led by One Health outcomes, and enacted through context-specific practices could represent a useful blueprint for sustainable PFP at the University of Edinburgh, and other public institutions.

Arriving at a set of common *values* and desirable *outcomes* for a university setting would be contingent upon dismantling several of the identified governance and human factor barriers of relevance to both universities and wider society. Such barriers have been identified by other authors, including Dixon and Isaacs (2013), who describe weak government policy as a barrier to the uptake of healthy and sustainable diets in Australia. In the current study, some key informants referenced policy incoherence and discordant opinion on food system goals as key barriers, stressing the need for higher welfare standards than those currently enshrined in University policy, which is a pertinent consideration for a university with esteemed veterinary and animal welfare groups. Furthermore, the University's Climate Strategy, committing to carbon neutrality by 2040 (The University of Edinburgh, 2020c), excludes food procurement from its scope. A holistic University strategy could be co-constructed to capture the values held by the institution's academic community as well as its leadership, and to capitalise on policy synergies and mitigate trade-offs across the One Health domains. In the food supply chain, direct partnerships and the provision of a reliable market for local producers could facilitate the development and

pursuit of mutually agreed outcomes, involving on-farm research - for example, around polyculture systems, and experiential learning.

Delivery of a future university food system in accordance with Figure 13 would also necessitate the pursuit of context-specific *practices*, and the dismantling of associated barriers relating to governance, human factors, and financial and social inequities. A review by Cruz *et al.* (2023) identified a series of barriers to sustainable and healthy food consumption, including a scarcity of affordable options, a lack of knowledge and awareness amongst the public about sustainability and its importance, a difficulty for consumers in distinguishing between products in terms of their sustainability credentials, and established dietary norms. In agreement with some of these consumption-side barriers, a range of initiatives were proposed by the key informants to enhance the social value derived from university food settings, as well as context-specific production-side initiatives including farm partnerships and standards reform (e.g., the development of inclusive, ambitious, and outcome-based standards; see Table 25). According to some informants, direct farm partnerships would necessitate specific actions such as adaptive menu setting, which may include less animal-source foods (Röös *et al.*, 2022) and more diverse food types that farmers are able to produce seasonally (van Zutphen *et al.*, 2022). To reflect these proposals, a One Health approach to university food procurement is displayed in Figure 14.

6.4.4 Limitations of this study and future prospects

Based on interviews with 20 key informants recruited through purposive sampling, this study represents a preliminary case study to illustrate the perceptions of a small group of university stakeholders, and will be subject to bias. This work could be interpreted as a primer to a larger and more detailed attitudinal survey or participatory workshops exercise involving a representative sample of the University community, to ratify the desired food system outcomes and suggestions for modifying the University's existing food system. Applying these findings more widely, larger studies to capture the perceptions of stakeholders from multiple higher education institutions could pave the way to a universities sustainable food framework and

purchasing collectives, providing a larger and more reliable market for producers contributing towards mutually-agreed outcomes for sustainability and regeneration.

6.5 Conclusions

The key informants' descriptions of RA were well aligned with their desired outcomes of the university food system, and with the University's strategy to '*make the world a better place*'. However, additional outcomes particularly relevant to university food settings included affordability, mental health, social cohesion, education, and leadership. RA descriptions and desirable outcomes mirrored the three One Health domains. Therefore, a framework inspired by RA values, led by outcomes to renew wellbeing across the One Health domains, and enacted through context-specific practices, could represent a useful blueprint to inform food services at universities and other public institutions. A series of recommendations are made to establish a set of common values and outcomes for the University food system, and to enact these through context-specific practices including standards reform, farm partnerships with aligned producers, and initiatives to enhance the social value of university food.

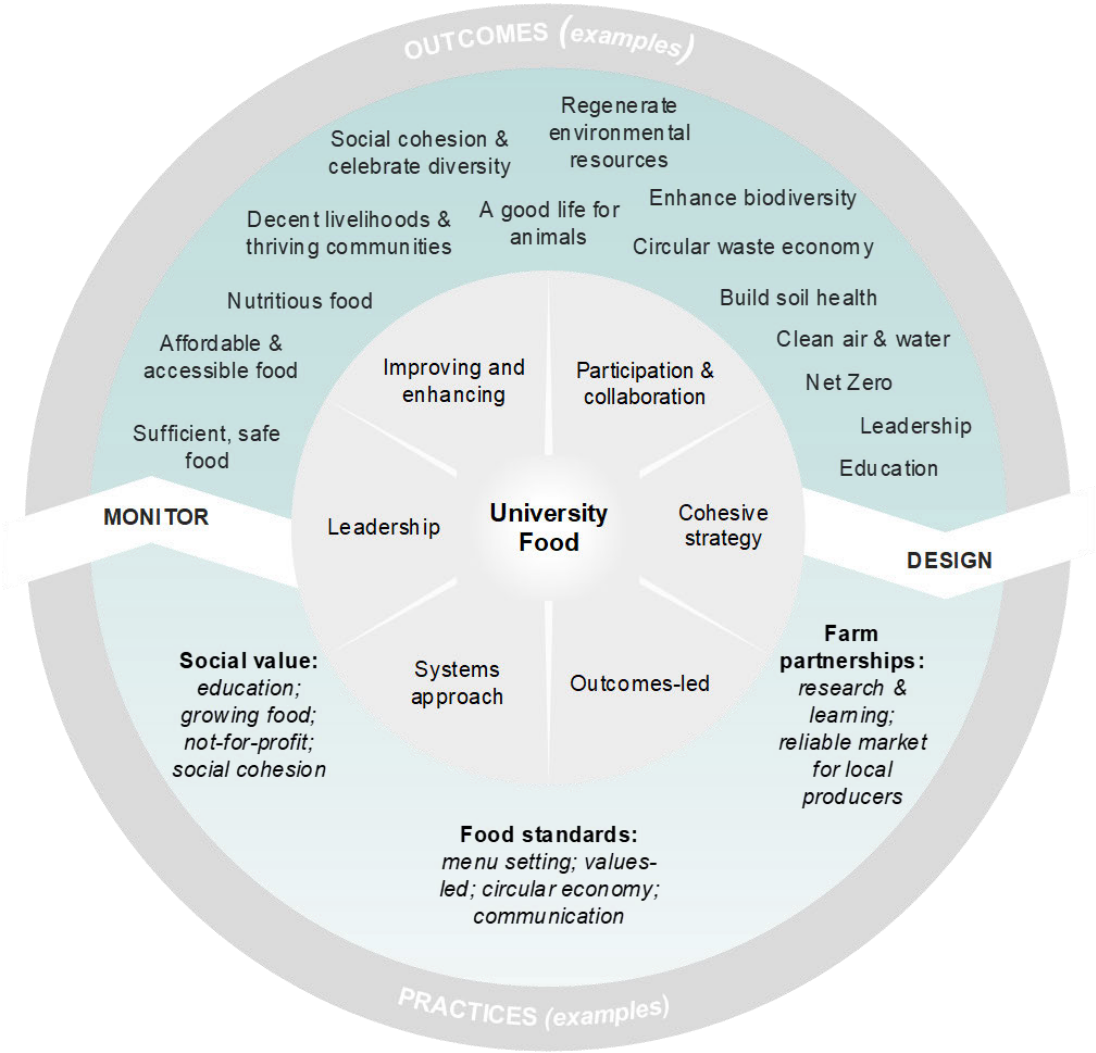

Figure 14: Characteristics of a future university food system, categorised into core values (central circle), outcomes, and practices based on thematic analysis of transcripts from 20 key informants from the University of Edinburgh community.

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Additional information: Disclosure statement

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6.6 Closing remarks

This final study moves from the production to the consumption-side of the supply chain, and returning to research question 1, indicates that animal wellbeing is a desirable food system goal and therefore a sustainability concern to the key informants interviewed. It illuminates an important role for public policy makers in calibrating public food policy with a sustainability agenda that incorporates the One Health domains including animal welfare, and an opportunity for universities to act as a beacon of food policy best practice. Finally, in response to research question 4, it presents a blueprint for food policy decision-making inspired by regenerative values, led by outcomes, and enacted through context-specific practices.

7. Conclusions and recommendations

This chapter discusses the value and contribution of this thesis to the fields of veterinary and agricultural sustainability, before identifying limitations to the research and recommendations for further studies.

7.1 Conclusions

This thesis explored the nexus between animal treatment and sustainability within the veterinary and agriculture sectors. It also aimed to clarify the roles of veterinary and agricultural stakeholders in the quest for more sustainable and equitable human-animal relations, in the frame of some alternative sustainability paradigms (e.g., weak versus strong sustainability).

In particular, it addressed four specific research questions: (1) Where or how are animal welfare and antimicrobial stewardship located in the sustainability agenda? (2) What are the roles of veterinary, agricultural, and public sector stakeholders in supporting animal welfare and antimicrobial stewardship as sustainability objectives? (3) What are the barriers to advancing animal welfare and antimicrobial stewardship as facets of sustainability? And (4) What actions could be taken to leverage the roles of veterinary and agricultural stakeholders in improving animal welfare and antimicrobial stewardship as dimensions of sustainability?

Chapter 2 summarises the spectrum of worldviews on sustainability, and finds that animal welfare problems and antibiotic resistance are arising as externalities from anthropocentric human-animal relations configured to generate market goods and services. Solutions to these problems can be particularly well-accommodated within ‘strong’ or ecological sustainability, and therefore animal welfare and antimicrobial stewardship can be considered to be integral to the sustainability agenda.

Subsequent chapters examine the animal treatment-sustainability nexus within four different settings, uncovering specific market failures within the veterinary and agricultural sectors due to tensions and trade-offs between One Health objectives. Veterinary and agricultural stakeholders operating at the human-animal-environmental interface hold key roles and opportunities to support more sustainable human-animal relations, by implementing relevant policies, practices, and equitable data sharing initiatives. Regulations are also crucial for addressing market failures, and public policy could strengthen the influence of veterinary and agricultural stakeholders as agents of sustainability by more effectively rewarding their delivery of public goods. Specific conclusions in relation to each of the research questions and the relevant stakeholders are summarised in Table 26 and in more detail in the following subsections.

Table 26: Key thesis conclusions based on the four research questions and the stakeholders to which they relate. Note, superscript numbers in this table refer to the chapters from which each conclusion was derived.

Research questions	Veterinary professionals	Agricultural stakeholders	Public policy makers
1. Where or how are animal welfare and antimicrobial stewardship located in the sustainability agenda?	The concepts of 'weak' and 'strong' sustainability both implicitly accommodate animal welfare and antimicrobial stewardship in their aims of maintaining intra- and inter-generational welfare flows, only differing in the extent to which capital stocks can be used and substituted for one another. Therefore, animal treatment concepts are theoretically integrated into either sustainability paradigm, but are particularly well-aligned with 'strong' or 'ecological' sustainability, which values the preservation of natural capital and interspecies wellbeing. However, the lack of explicit inclusion of animal welfare and antimicrobial stewardship in international frameworks and metrics, deprioritise these sustainability domains. Therefore, animal welfare problems and antimicrobial use and resistance arise as negative externalities of modern human-animal relations, for example, within the commercial food system.[2]		
2. What are the roles of veterinary, agricultural, and public sector stakeholders in supporting animal welfare and antimicrobial stewardship as sustainability objectives?	○ Leadership and public advocacy to incorporate human, animal, and environmental objectives into the sustainability discourse; in particular, to champion the importance of animal welfare and antimicrobial stewardship as neglected domains[3] ○ Create sustainable veterinary workplaces and operations; e.g., staff mental wellbeing, environmental footprints, protecting the welfare of animals under veterinary care, and medicine stewardship[3,4] ○ Provision of services that improve the sustainability of animal care and production[3] ○ Animal owner/client education[3] ○ Provision of professional training and education[3,6] ○ Protecting public health and food safety[3] ○ Disease surveillance and control[3] ○ Product and technology innovations[3] ○ Social interventions and collaborations; e.g., green/social prescribing, and responding to signs of domestic abuse[3]	◦ Implementing food production practices that deliver positive sustainability outcomes across the human, animal, and environmental domains[2,4,5,6]	◦ Devising public policy that delivers optimal public good outcomes for society, including on animal welfare and antimicrobial use[2,6]

Research questions	Veterinary professionals	Agricultural stakeholders	Public policy makers
3. What are the barriers to advancing animal welfare and antimicrobial stewardship as facets of sustainability?	○ Lack of guidelines and information to guide sustainable policies and practices[3] ○ Conflicting sustainability objectives[4,5]; tension between opposing private and public interest claims, and inadequate reward for the delivery of public goods[2] ○ Gaps in social wellbeing policies and practices in veterinary workplaces, and veterinary mental health problems[3]	○ Conflicting sustainability objectives; tension between opposing private and public interest claims, and inadequate reward for the delivery of public goods[2,6] ○ Inadequate levers within the private sector (e.g., farm certification) and limited market traction for higher animal welfare products, particularly relating to positive mental wellbeing[2,6] ○ High production costs; low food prices[6] ○ Dominant and normalised production systems and breeds selected for economic performance, representing drivers of animal welfare problems and antibiotic use[2,5] ○ Challenges in gathering data from numerous stakeholders in the supply chain, and utilising and benefiting from this equitably[5]	○ Conflicting perspectives to reconcile when establishing public policy and statutory thresholds for animal welfare; e.g., scientific evidence, public sentiment vs. consumer willingness-to-pay, i.e., the 'consumer-citizen duality', public food and nutritional security and affordability, and farmer livelihoods[2,5] ○ Lack of international policy, governance, and harmonised systems around antimicrobial use and resistance[2]
4. What actions could be taken to leverage the roles of veterinary and agricultural stakeholders in improving animal welfare and antimicrobial stewardship as dimensions of sustainability?	○ Voluntary initiatives; e.g., self-regulation, guidelines and information, self-assessments, standards, accreditation, education, and use of multi-criteria decision-making tools[3,4,5] ○ Voluntary initiative to develop or support the use of robust and equitable data-sharing systems, to collect, analyse, and monitor data on sustainability outcomes within animal-based settings (e.g., food supply chains)[5] ○ Market-based instruments; e.g., performance bonds issued by veterinary organisations to veterinary suppliers to ensure they fulfil sustainability obligations[3]	○ Voluntary initiative to create consensus-based sector-specific sustainability metrics on which to base multi-criteria decision-making, including indicators of positive human, animal, and environmental wellbeing[3,4,5] ○ Voluntary initiative to create evidence-based guides on best practice in animal and waste management to mitigate ecological impacts of medicines[4] ○ Voluntary initiative to develop/support robust and equitable data-sharing systems with user-friendly farmer interfaces, to routinely benchmark units, reward relative best performers, and inform supply chain policy for continuous improvement[5] ○ Voluntary initiative to create a food certification model with outcome-based, ambitious, and context-specific criteria, and with clear and transparent citizen messaging[6]	○ Explicit inclusion of human, animal, and environmental wellbeing within sustainability definitions, frameworks, and metrics[2,3,4,5,6]. ○ Use of multicriteria decision tools to identify, incentivise, and reward positive outcomes of food production across the One Health domains[4,5,6] ○ Provision of grants and incentives to support the delivery of public goods by veterinary and agricultural stakeholders[3] ○ Applying relevant regulatory instruments to the veterinary and agriculture sectors; e.g., increased welfare standards, codes of practice, emissions standards, reporting requirements such as outcome measures relating to veterinary workplaces and animals under veterinary care[3,4] ○ Applying coherent standards and frameworks to public food procurement settings that reflect domestic policy for human, animal, and environmental wellbeing, and provide a PFP market for sustainable UK produce[6]

7.1.1 Veterinary professionals

Roles

As gatekeepers of animal welfare and antibiotic use, veterinary professionals are crucial custodians of all aspects of animal treatment. Chapter 3 describes how animal welfare and medicine use policies are reportedly in place at most of the veterinary centres surveyed across the UK and Republic of Ireland, indicative of strong policy commitment to these issues. Reflecting on Chapters 2, 3, and 4, veterinary professionals could be crucial agents in the quest for a more ecological approach to sustainability, supporting positive outcomes across the One Health domains. Table 26 consolidates the roles of veterinary professionals in the sustainability context from Chapter 3, including but not limited to leadership and advocacy, sustainable workplaces and operations, animal owner education, product innovation, and social interventions.

Barriers

Notwithstanding these observations, policies and practices reported in Chapter 3 across the environmental, social, and animal welfare domains were variably enacted, indicative of a burgeoning but fragmented approach to sustainability amongst veterinarians and their workplaces. Respondents pointed to a barrier and an unmet need for information and guidance around sustainable practices to fill the value-action gap.

Antibiotics pose specific challenges across the One Health domains, yet Chapter 2 describes the dominant public health framing of antimicrobial stewardship in the global discourse, which to date has neglected the ecological dimensions of antibiotic use in terms of its variable impacts on non-target organisms, highlighted in Chapter 4. The risk matrix presented in Figure 10 points to a tension between One Health objectives, that is yet to be navigated in the stewardship of antibiotics in the veterinary and agriculture sectors – representing a barrier to incorporating antimicrobial stewardship into the wider sustainability agenda.

Such conflicts of interest may be experienced by veterinary professionals in relation to competing public-private interests. In their service of the private animal industries, the ability of veterinary professionals to improve animal treatment, e.g., to facilitate positive affective states, may also at times be constrained by low regulatory welfare baselines, high husbandry and treatment costs, consumer demands (e.g., for cheap food), and private interests. Delivery of public goods beyond regulatory requirements by veterinary professionals is evident in the multiple positive externalities arising from veterinary work (e.g., Devitt *et al.*, 2013; Lovatt, 2015). However, inadequate rewards for these efforts may, in some cases, allow private interests to influence decisions, which could in turn harm the profession's social license (Hampton *et al.*, 2020). The personal and financial costs absorbed by veterinary professionals associated with delivering additional public goods and navigating these conflicts of interest could be significant, representing a possible driver of the notably poor mental health within the veterinary sector (Mellanby, 2005). Chapter 3 suggests that staff at veterinary centres are not always formally supported in terms of their mental health, with wellbeing policies and practices enacted by only a minority of workplaces. Future research could explore the possibility that mutually reinforcing links exist between poor mental health amongst veterinary professionals and their challenges in delivering public goods, particularly those upholding animal and ecological wellbeing.

Actions

Voluntary initiatives will be important in leveraging the multifaceted role of veterinary professionals to advance the sustainability agenda; for example, policies, accreditation, use of multi-criteria decision-making tools, and data-sharing initiatives (see Table 26). As mentioned in Chapter 3, market-based instruments could also be valuable, for example in the corporate veterinary group context, to ensure suppliers are delivering against environmental obligations. Representing another market failure within the sector, concerns of corporate monopolisation and resultant impacts on pet owners and veterinary staff is currently the subject of a Competition Marketing Authority (CMA) investigation into the UK small animal veterinary industry. As part of voluntary self-regulation, further research is needed to explore alternative veterinary service delivery models that solve these market failures, and retain and strengthen the sector's social license.

7.1.2 The agriculture sectors

Role

Agricultural stakeholders, i.e., producers, processors, retailers, and other food business actors, hold vital roles in integrating animal welfare and antimicrobial stewardship into the sustainability agenda and metrics. Indeed, such stakeholders – particularly farmers – are at the coalface of food production that can deliver positive sustainability outcomes across the human, animal, and environmental domains. FAWC (2007) describes stockmanship as "*the single more important influence on the welfare of farmed animals*". Chapter 4 describes the success of the UK agriculture sector in reducing antimicrobial use on public health grounds, in-part due to concerted data collection and target-setting by sector-specific working groups as part of the RUMA Targets Task Force (FAO and VMD, 2022; RUMA, 2023)

Barriers

Mirroring conclusions from the veterinary sector, conflicting sustainability imperatives in the form of opposing public/private interest claims on resources, represent a barrier to sustainability practices that incorporate animal welfare and antimicrobial stewardship in agriculture. i.e., when producers and supply chains focus on single sustainability outcomes (e.g., productivity and efficiency), trade-offs for other sustainability domains can emerge (e.g., animal welfare and antimicrobial stewardship). As examples, Chapter 4 traces the lesser-known ecological impacts of the current antibiotic usage regimes that support public health outcomes. Inadequate support for farmers for delivering public goods was considered a barrier to attaining food system outcomes by key informants interviewed in Chapter 6.

Beyond legal minimum thresholds, farmed animal welfare and antimicrobial stewardship are delivered through private market transactions, and are codified in retailer standards and food assurance scheme labels. However, Chapters 2 and 6 suggest these levers are inadequate, for example in terms of fostering 'good life' opportunities for all farmed animals and protecting ecological resources from antimicrobial residues. The barriers to advancing sustainability practices are reinforced by limited market traction for higher welfare food products, high production costs, and low food prices, as discussed in Chapter 6.

Chapter 5's conclusions support the notion that laying hen breeds with balanced genetic merit will play an important role in food systems seeking to mitigate multiple externalities of production. Although this conclusion aligns with other studies and sectors (e.g., Oltenacu and Broom, 2010), the dominant use of production-oriented breeds - often justified on the grounds of food security and resource use efficiency - remains a barrier to animal welfare potential in some agricultural settings (Hartcher and Lum, 2020).

The market dominance of production-oriented breeds exemplifies some systemic barriers to sustainable human-animal relations. Indeed, such barriers may constrain progress on animal welfare, and also antimicrobial stewardship within animal agriculture, suggested by the marked reductions followed by plateauing in antibiotic usage levels in some sectors (e.g., British Poultry Council, 2022) as they reach a notional 'glass floor'. Dismantling systemic barriers, such as dominant production-oriented breeds and intensive production practices is likely to play a crucial role in lowering antibiotic use to below this 'glass floor' threshold, and similarly enhance animal welfare and environmental outcomes.

Data collection, analysis, benchmarking, and evidence-based decision-making can support the pursuit of sustainability objectives. However, Chapter 5 concludes that such programmes are contingent upon reliable and often hard-to-reach datasets relating to multiple indicators monitored over the lifecycle of several comparable farm units. Data collection is therefore a barrier to data-centric approaches, and there is a danger that such projects sponsored by the most influential supply chain actors, e.g., retailers, demand time and resources from farmers with inadequate compensation and benefit for the farmers.

Actions

The use of multi-criteria decision-making tools as a voluntary initiative by agricultural stakeholders, as demonstrated in Chapter 5, can accommodate animal dimensions within evaluations of food systems and can be used to inform best practice and supply chain policy. In this study, Data Envelope Analysis is used to benchmark free-range laying hen flocks within a commercial egg supply chain, uniquely incorporating environmental, economic, *and* animal treatment criteria to inform production systems

and policies. This study offers a template for objectively isolating and incentivising the production system characteristics that can reward the delivery of a balanced suite of sustainability objectives within animal-based settings (e.g., farms). Using this approach, the systemic barriers to sustainable production (e.g., production systems and production-oriented breeds) could be objectively identified and addressed. It would, however, depend on equitable data-sharing platforms involving and benefiting all actors within the agricultural supply chain, and a sector-level consensus on the most salient indicators (inputs and outputs) for inclusion in species-specific multi-criteria sustainability metrics. Such criteria could include indicators of positive impacts, such as human and animal mental wellbeing, and ecological regeneration. In line with multi-criteria approaches, Chapter 4 highlights an opportunity for agricultural actors to realign their successful antimicrobial stewardship efforts with the One Health framework, utilising the Risk Matrix shown in Figure 10.

Specific recommendations for protecting ecosystems from the harmful impacts of certain antibiotic residues can be gleaned from Chapter 4. For example, a voluntary initiative could be established to create evidence-based guidelines to inform best practice in animal and waste management following antibiotic use on farms. Although statutory data-sheet recommendations are presented within drug packaging, additional and user-friendly guidance could also draw from the increasing body of research that proposes interventions such as storing manure for a minimum of six months prior to spreading it on land, to allow the degradation of antibiotic residues and AMR determinants.

Further actions within the agriculture sector could address findings from Chapter 6, which identified both production and consumption-side challenges with the current model of farm/food certification and their support of desirable food system outcomes. It is proposed that a voluntary system of food certification could be designed with outcome-based, ambitious, and context-specific criteria, and with clear and transparent citizen messaging, to segment the market in line with niches such as regenerative agriculture.

7.1.3 Public policy-makers

Role

A key role for governments and public policy makers is in defining the statutory thresholds for the delivery of public goods by the private sector, to reflect where the publics' preferences are thought to lie (as described in Chapter 2). These thresholds include those relating to animal welfare and antimicrobial use and stewardship in the food sector. Furthermore, public policy makers are responsible for establishing public food procurement frameworks for food service in higher education settings (e.g., as described in Chapter 6), as well as in schools, care homes, hospitals, military canteens, and prisons. These policies represent important levers for driving sustainability in the UK food system, and providing a market for UK farmers.

Barriers

However, in some communities and settings, these 'public preferences' are ill-defined. Similarly, within some public and private sector contexts, procurement objectives may be misaligned with the needs and desires of its consumers. Chapter 6 describes how the food outcomes desired by members of a university community bridged all three of the One Health domains, with the specific outcomes of affordability, mental health, social cohesion, food system leadership, and education highlighted for universities. Amongst other objectives, a good life for animals was considered a desirable food system outcome, affirming its position as a sustainability concern in the university context. However, in wider society, the gap between citizen concern about farmed animal welfare and consumer purchasing decisions is well documented (i.e., the 'consumer–citizen duality', Vanhonacker et al (2007), Chapter 2), suggesting an inability or unwillingness amongst consumers to buy products matching their animal welfare values. Rather than signalling low public support for higher animal welfare standards, this paradox represents the failure of the market to reflect the cost of providing public goods, as well as individual inability to clearly distinguish and pay for public good attributes in food products. Similar to the barriers encountered by veterinary and agricultural stakeholders, public policy makers have these multiple and sometimes conflicting sustainability perspectives to reconcile, which may hamper policy making.

In the case of antimicrobial stewardship, barriers also include a lack of international governance, which places demands on individual states to create discrete antimicrobial action plans and reporting systems.

Actions

Defining sustainability as a broad concept that explicitly includes human, animal, and environmental dimensions will be important in driving more sustainable human-animal relations through UK public policy. Alongside the collection and analysis of outcome measure data from veterinary and agricultural stakeholders relating to animal care, multi-criteria decision tools could be applied at government level to identify and incentivise best practice, and reward the delivery of positive sustainability outcomes and public goods in UK food production. Such tools do not discriminate between production systems, and can be applied to those within 'sustainable intensification' contexts as well as agroecological and regenerative settings. Their results can therefore transcend polarised debates around farming systems, objectively informing a transition towards a better food system that accounts for the wellbeing of all species and ecosystems.

Grants and incentives for farmers could support their delivery of public goods, building on and enhancing those that are increasingly being offered through ELMS and the Sustainable Faming Incentive (SFI) (UK Government, 2024a). Incentives and rewards for embedding public goods delivery into private veterinary business models could also represent an important means of addressing market failures around animal treatment outcomes, particularly within a corporatised veterinary sector experiencing increased pressure to maximise private gain over social value. It is postulated that such interventions may also begin to address some of the mental health challenges experienced within these communities.

Because markets are unable to fully deliver public goods relating to animal welfare and antibiotic environmental impacts, government intervention is also warranted in the form of regulatory instruments; e.g., higher minimum legal standards for animal welfare, including mental wellbeing and positive affective states, to match government policy with public sentiment in the UK, buttressed by professional, financial, and social support for farmers during this transition. Applying standards

and frameworks to public food procurement settings that reflect these domestic policies for human, animal, and environmental wellbeing would foster policy coherence and provide a market for sustainable UK produce. In contrast to animal welfare issues, antimicrobial use in farmed animals has been effectively reduced within private markets with minimal government intervention. However, owing to the public health framing of the problem, negative ecological externalities are coming to light, necessitating a new One Health contextualisation of the issue (e.g., Figure 10) to inform government and private sector decision-making. Government surveillance, mapping, and regulation around medicine residues in human/animal waste and environmental compartments, as identified in Chapter 4, could help to mitigate and monitor these impacts.

7.1.4 Common theme

A key theme can be distilled from this diverse collection of studies: anthropocentric worldviews remain predominant in sustainability decision-making to the detriment of animal welfare and ecosystems, including within the animal-based sectors. In the process of converting 'resources' (including non-human animals and natural resources) into market goods and services, externalities arise from supply chains including welfare harm to sentient animals and the depletion of exhaustible resources (i.e., non-renewable natural resources and semi-renewable antimicrobial efficacy).

Figure 15 situates the key themes of animal welfare and antimicrobial use within the wider landscape of the modern food system, and proposes that the fundamental drivers of antimicrobial use and animal welfare problems in farmed animals can be traced to the growing demand for animal protein and the pursuit of resource use efficiencies, which generate proximate drivers in the form of intensive husbandry and management practices (Delgado *et al.*, 1999; Bessei, 2006; Van Boeckel *et al.*, 2015; Murphy *et al.*, 2017). This helps to identify potential levers for unlocking solutions to improving both dimensions of animal treatment, with particular relevance to the policies and practices implemented at farm, processing, and retailer levels. It illustrates that the majority of antibiotics are used in UK/EU farmed animals to control

animal welfare externalities, and therefore antimicrobial stewardship is contingent upon improving welfare outcomes. In turn, these welfare externalities are driven by a small number of proximate (production system) and fundamental causes, which could be addressed through food system reform involving a reduction in animal protein production and consumption, coupled with higher welfare policies and practices.

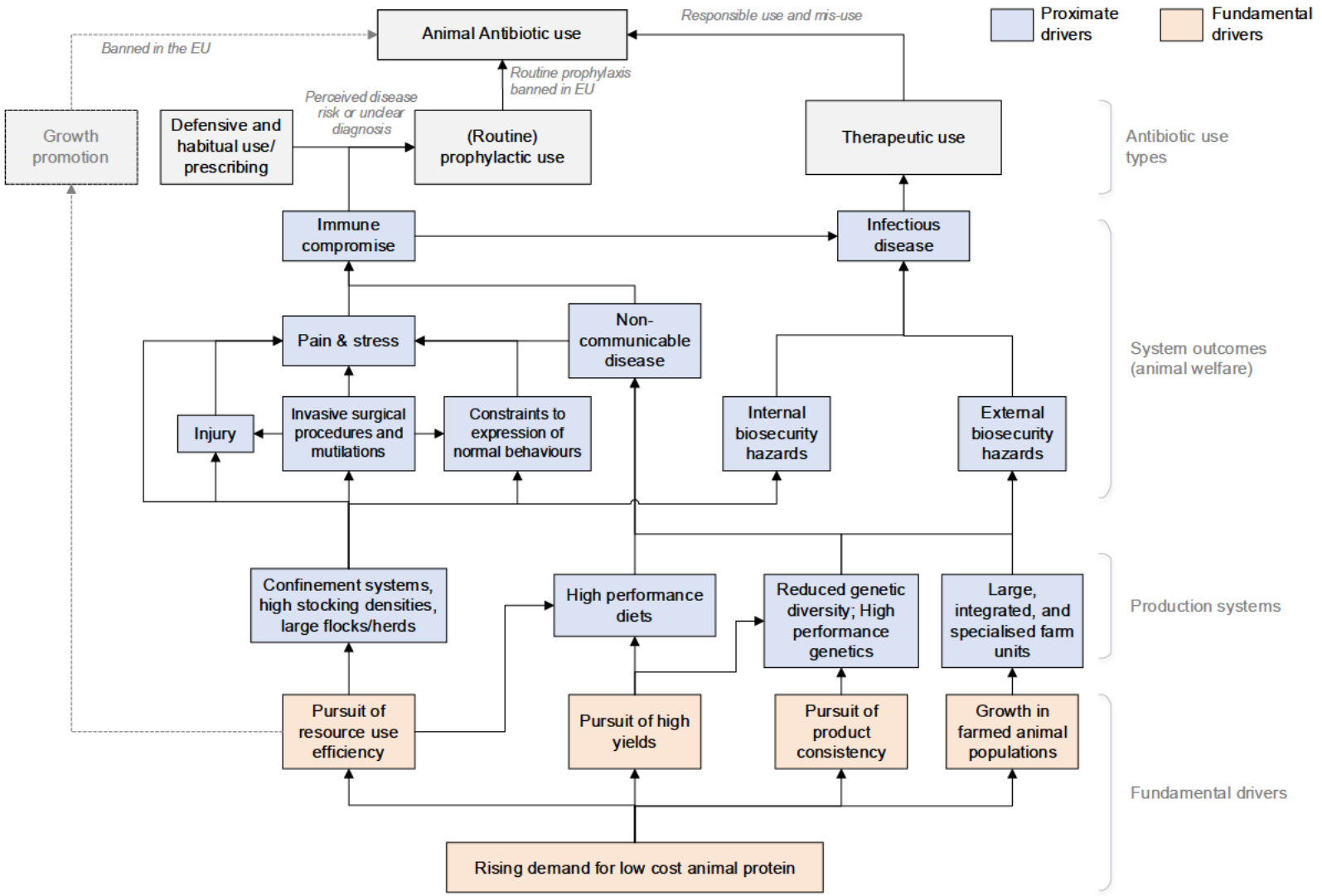

Figure 15: Fundamental and proximate drivers of antibiotic use and animal welfare problems in animal agriculture.

7.1.5 Contribution to the literature

This collection of studies contributes to the sustainability literature within the veterinary and agricultural fields, by highlighting market failures within these animal-based sectors, in terms of animal and environmental wellbeing. It affirms the position of animal welfare and antimicrobial use as facets of sustainability, which can be accommodated within the weak and strong sustainability paradigms. As well as highlighting the key roles of veterinary and agricultural stakeholders, it identifies several production and consumption-side barriers to incorporating animal treatment concerns in to the sustainability agenda. Finally, it demonstrates and proposes a series of frameworks to more accurately account for these externalities, by incorporating a balanced One Health approach including animal treatment considerations, into public and private sector decision-making. These frameworks include the set of programmes, incentives, and policy instruments for the veterinary professions displayed in Table 9, the novel One Health matrix for antibiotic stewardship in Figure 10, the use of data envelope analysis uniquely incorporating animal welfare and antibiotic use metrics as demonstrated in Chapter 5, and the One Health approach to university food procurement, illustrated in Figure 14.

7.2 Limitations

The methodological limitations of the individual studies are detailed in the relevant chapters. However, during this PhD some noteworthy ‘macro’ constraints were encountered.

Firstly, data access became a problem due to the commercial control and sensitivity of sustainability data, such as that relating to animal welfare and antibiotic use. The first two years of this PhD involved building a commercial partnership and analysing a large poultry dataset, after which permissions for further analysis and publication were withdrawn by the company. This set-back cost significant time; however, a rapidly-established partnership with an egg processing company, facilitated by FAI, allowed deployment of the same methodological approach but with an alternative

dataset (Chapter 5). This problem is symptomatic of the control by commercial entities (e.g., food brands) over sustainability data, which carry valuable public good characteristics.

On a personal note, these studies were interrupted by the COVID-19 pandemic, necessitating a three-month break from study for childcare in 2020, and further months of illness interruptions thereafter. Notwithstanding these issues, a COVID extension and flexibility was kindly granted by supervisors and the University, allowing completion of this thesis.

7.3 Future research

Opportunities for further research are numerous within this field of study. However, future projects could prioritise the levers for practically delivering public goods related to animal treatment within veterinary and agricultural settings. One study could explore alternative futures for veterinary service delivery, beyond the corporate model, that enable and incentivise the attainment of balanced One Health outcomes. Another could elaborate on the One Health matrix in Chapter 4, building a more detailed picture of the One Health impacts of the individual antibiotics used in UK farmed species, and mapping solutions for mitigating their use, discharge, hot spots, and ecological impacts. Finally, a project could build upon Chapter 5, using expert elicitation to compile a set of outcome measures across the One Health domains for food production, including indicators of regeneration, and apply these criteria using DEA within a range of production systems and supply chains for benchmarking and to inform policy.

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Supplementary Materials

Chapter 3

Veterinary practice sustainability survey questions

	Question	Response options
1	What is your current role or position? *(tick all that apply)*	Veterinary surgeon / Veterinary nurse / Veterinary student / Trainee veterinary nurse / Animal assistant / Technician / Receptionist / Practice manager / Practice owner or partner / Clinical director, director or other member of the leadership team / Other (please specify)
2	What type of veterinary organisation do you currently work for? *(tick all that apply)*	Small animal and exotics / Equine / Farm animal / Mixed practice / First opinion / Specialist referral clinic / Teaching institution / Government / Industry / Charity / Locum / Retired / Other (please specify)
3	What is the name and location of your practice? *NB: This question is optional. This information, if provided, will be used to ensure we account for duplicate submissions from the same practice in our analysis and this information will not be used for any other reason.*	Free text field: Practice name / Postcode
4	Does your practice have a documented environmental policy?	Yes / No / Don't know
5	If yes, what areas does your environmental policy include? *(tick all that apply)*	Publicly available policy statement / Energy usage / Carbon footprint information / Carbon offsetting / Water usage / Transport (e.g., commuting, travel in company vehicles, supporting walking/cycling and use of public transport) / Recycling and waste segregation / Reduction in usage of packaging and single-use items / Paper usage (source, use, disposal) / Anaesthetic gases / Chemicals e.g., cleaning materials, sterilising fluids, radiography developers / Procurement of supplies / Food procurement and/or disposal / Medicine use (waste reduction; ecotoxicity of antiparasitics) / Environmental building design and infrastructure / On-site biodiversity and green spaces / Client education / Legal compliance / Monitoring and reporting / Staff engagement / Community projects / External accreditations / Preventive medicine / Don't know / Other (please specify)

6	If no (to Q4), does your practice do any of the following to support the environment? *(tick all that apply)*	Only use renewable energy suppliers / Actively try to reduce water usage / Offset the practice's carbon emissions / Recycle waste / Actively reduce packaging / Only use recyclable packaging where possible / Only use sustainable paper / Other (please specify) / None of the above
7	If no (to Q4), what might encourage your practice to adopt and implement an environmental policy? *(tick all that apply)*	Clear leadership, strategy and goals from senior management / Clear demonstration of the financial benefits to the practice of having an environmental policy / Standards, guidance and frameworks for practices to follow / Regulation / More time/personnel / Dedicated budget / Support from members of the team / Greater knowledge on sustainable solutions for veterinary practices / Environmental accreditation and public endorsement / Other (please specify)
8	On a scale of 1 to 5, how aware are you of legal and regulatory requirements relating to sustainability, and their impact upon veterinary practice, where 5 is fully aware and 1 is not at all aware?	1 - not at all aware / 2 / 3 / 4 / 5 - fully aware / Free text field: Additional comments
9	Does your practice have a policy on antibiotic use and stewardship?	Yes / No / Don't know
10	If yes, which of the following does your antibiotic use and stewardship policy include? *(tick all that apply)*	Treatment protocols/guidelines / Policy around prophylactic use / Requirement to use antibiotic alternatives in certain circumstances / Infection control and hygiene procedures and practices / Client education/supporting client compliance / Protocols for storage and disposal of antimicrobials / Protocols requiring diagnostic testing to guide antibiotic selection / Guidelines on use of specific antimicrobials / Restrictions on use of specific antimicrobials / Adoption of professional guidelines (e.g., BVA's 7 Point Plan) / Monitoring antibiotic usage / Other (please specify) / None of the above
11	If no (to Q9), does your practice have any of the following (tick all that apply):	Antibiotic treatment protocols/guidelines / Policy around prophylactic use of antibiotics / Requirement to use antibiotic alternatives in certain circumstances / Infection control and hygiene procedures and practices / Client education/materials around reducing antibiotic use / Protocols for storage and disposal of antimicrobials / Protocols requiring diagnostic testing to guide antibiotic selection / Guidelines on use of specific antibiotics / Restrictions on use of specific antimicrobials antibiotics / Monitoring of antibiotic usage / Other (please specify)
12	If no (to Q9), what might encourage your practice to adopt and implement an antibiotic use and stewardship policy? *(tick all that apply)*	Clear leadership, strategy and goals from senior management / Clear demonstration of the benefits to public health/animal health / Standards, guidance and frameworks for practices to follow / Regulation / More time/personnel / Dedicated budget / Support from members of the team / Greater knowledge and interest within the team / Public endorsement or accreditation / Other (please specify)

13	Does your practice have a policy on the use of medicines for parasite control?	Yes / No / Don't know
14	If yes, which of the following does your policy on the use of medicines for parasite control include? *(tick all that apply)*	Treatment protocols/guidelines / Guidelines surrounding prophylactic use of parasiticides / Requirement for pre-treatment diagnostic testing for parasites before prescribing / Risk assessments for use in individual patients / Use of anti-parasitic alternatives / Client education/supporting client compliance / Protocols for storage and disposal of products / Guidelines on the use of specific parasiticides / Restrictions on the use of specific parasiticides / Other (please specify)
15	If no (to Q13), does your practice do any of the following in relation to parasite control? (tick all that apply).	Have specific treatment protocols / Have documented guidelines surrounding prophylactic use of parasiticides / Require pre-treatment diagnostic testing for parasites before prescribing / Carry out risk assessments for use in individual patients / Recommend the use of anti-parasitic alternatives / Provide materials to educate clients about anti parasiticides / Have documented protocols for the storage and disposal of antiparasiticide products / Have guidelines or restrictions on the use of specific parasiticides (please specify which) / None of the above
16	If no (to Q13), what might encourage your practice to adopt and implement a policy on the use of medicines for parasite control? (tick all that apply)	Clear leadership, strategy and goals from senior management / Clear demonstration of the benefits to public health/animal health / Standards, guidance and frameworks for practices to follow / Regulation / More time/personnel / Dedicated budget / Support from members of the team / Greater knowledge and interest within the team / Public endorsement or accreditation / Other (please specify)
17	Does your practice have an animal welfare policy or policies on specific welfare issues?	Yes / No / Don't know
18	If yes, what aspects does your animal welfare policy include? *(tick all that apply)*	Housing and nutrition for kept animals / Environmental enrichment and normal behaviours in kept animals / Animal companionship/grouping animals where appropriate / Breeding and genetics / Breeding establishments / Surgical mutilations / Management of welfare cases / Animal handling and reducing stress / Pain management / Emergency euthanasia / Support for ethical decision-making / Other (please specify)
19	If no (to Q17), does your practice have any specific guidelines in relation to any of the following aspects of animal welfare? (tick all that apply)	Housing and nutrition for kept animals / Environmental enrichment and normal behaviours in kept animals / Animal companionship / grouping animals where appropriate / Breeding and genetics / Breeding establishments / Surgical mutilations / Management of welfare cases / Animal handling and reducing stress / Pain management / Emergency euthanasia / Other (please specify) / None of the above

20	If no (to Q17), what might encourage your practice to adopt and implement an animal welfare policy? *(tick all that apply)*	Clear leadership, strategy and goals from senior management / Clear demonstration of the benefits / Standards, guidance and frameworks for practices to follow / Regulation / More time/personnel / Dedicated budget / Support from members of the team / Greater knowledge and interest within the team / Public endorsement or accreditation / Other (please specify)
21	On what animal welfare topics you would be interested in receiving further training?	Free text field
22	Does your practice occasionally, regularly or routinely advise clients on environmentally responsible animal husbandry?	Yes / No / Don't know
23	To which species does your environmentally responsible animal husbandry advice apply? *(tick all that apply)*	Cats and dogs / Exotic pets / Horses/equids / Farmed livestock / Farmed fish / Wild captive animals / Other (please specify)
24	Please describe or provide examples of your advice to clients on environmentally responsible animal husbandry.	Free text field
25	Does your practice have a policy relating to social sustainability or policies on specific social issues (including health and safety, modern slavery, inclusion and diversity, volunteering)?	Yes / No / Don't know
26	If yes, which of the following does your policy on social sustainability include? *(tick all that apply)*	Modern slavery / Inclusion and diversity / Tools and processes that support fair and equitable recruitment and conditions of work with no tolerance of discrimination, bullying or harassment / Health and safety / Transparency and equity in the supply chain of materials, resources and services / Fair and regular employment conditions detailed in written contracts / Wellbeing initiatives and/or mentorship for team members / Staff time allocated for voluntary activities or projects, in/outside the workplace / Other (please specify)
27	If no (to Q25), what might encourage your practice to adopt and implement a social sustainability policy? *(tick all that apply)*	Clear leadership, strategy and goals from senior management / Clear demonstration of the benefits / Standards, guidance and frameworks for practices to follow / Regulation / More time/personnel / Dedicated budget / Support from members of the team / Greater knowledge and interest within the team / Other (please specify)
28	Which of the following sustainability concerns do you feel most strongly about? *(tick all that apply)*	Animal welfare / Carbon emissions / Deforestation / Environmentally sustainable animal ownership / Modern slavery issues / Supporting local communities / Wildlife and environmental conservation

29	Vet Sustain aims to enable and inspire veterinary professionals to drive sustainability in their roles. What could they do to help you to drive sustainability in your workplace?	Free text field
30	Select the three projects from the following list that you think Vet Sustain should prioritise in order to support sustainability in veterinary practices.	Online sustainability toolkit for practices (to include legal/regulatory information for practices) / Online toolkits to support sustainable animal ownership (farm, equine, pet, exotic) / Toolkits for reducing the environmental footprint of practices / Webinars on environmental topics / Training days, events or conferences / Consensus guidelines published in scientific journals / Blogs and case studies for inspiration / Engagement with professional bodies and corporate groups / Engaging with the vet schools to make sustainability explicit in the undergraduate curriculum / Supporting a network of sustainability 'champions' across the profession to drive projects at local level / Other
31	In which of the following sustainability subject areas would you be interested in receiving further training? *(tick all that apply)*	Environmental management in the clinic/workplace / Sustainability – the legal and regulatory landscape for veterinary practices / Responsible medicine uses to mitigate antimicrobial resistance / Responsible medicine uses to mitigate ecotoxicity / Wildlife and environmental conservation / Sustainable/ regenerative food animal production / Environmentally responsible pet ownership (small animals and exotics) / Environmentally responsible horse ownership / Animal welfare topics / Social sustainability / Other (please specify) / None of the above

Table A Laying hen feather scoring chart based on AssureWel guidelines (from FAI Farms, adapted from AssureWel (2013)).

Feather score 0	Feather score 1	Feather score 2
 	 	 
No/minimal feather loss: No bare skin visible, no or light wear, only single feathers missing.	**Slight feather loss**: Moderate wear, damaged feathers or 2 or more adjacent feathers missing up to bare skin visible < 5cm (2 inches) maximum dimension.	**Moderate feather loss**: Bare skin visible more than or equal to 5cm (2 inches) maximum dimension.

Table B Comparison of standards in UK free range and organic flocks. Free-range flocks in this study are certified by RSPCA Assured (RSPCA, 2017), and organic flocks are assured by both RSPCA Assured and Organic Farmers and Growers (Organic Farmers and Growers, 2013). All flocks are legislated by the UK Government's Animal and Plant Health Agency (APHA, no date).

Standard	**Free-range flocks** *(RSPCA Assured; APHA)*	**Organic flocks** *(RSPCA Assured; OF&G; APHA)*
Group size	Maximum flock size of 16,000 hens; maximum colony* size 4,000 hens.	Maximum flock size of 3,000 hens
Stocking density	9 hens/m^2 in the house.	6 birds/m^2 in the house.
Feeding	Appropriate feed including grit, and extra fibre when required. 10cm linear trough space/4cm circular trough space/hen.	Roughage, fresh or dried fodder, or silage must be added to daily rations. 10cm linear trough space/4cm circular trough space/hen.
Substrate	Minimum litter cover of 250sqcm per hen and must cover 1/3rd of the ground surface.	Minimum litter cover of 250sqcm per hen and must cover 1/3rd of the ground surface.
House design	Maximum of 4 levels (including floor); hens must be able to move freely between the tiers; headroom above each level 45cm, with feed and water distributed between levels	Maximum of 4 levels (including floor); hens must be able to move freely between the tiers; headroom above each level 45cm, with feed and water distributed between levels
Enrichment in house	15cm/perch space/hen; 5 hens/nest or 1m^2/120 hens; 2 items of enrichment per 1,000 hens.	18 cm perch/hen; 5 hens/nest˜ or 120cm^2/hen.
Lighting	A minimum of 8 hours continuous light and minimum of 6 hours continuous darkness every 24-hour cycle	16 hours light/day with a continuous nocturnal rest period of at least 8 hours
Range access and stocking density	Continuous daytime access to a range from 21 weeks (latest). Maximum stocking density 2,500 hens/ha. 2m of pop-hole access/1000 hens.	Open-air range access for at least 1/3 of hens' lives. Maximum stocking density 4m^2 per hen (2,500/ha). 2m of pop-hole access/1000 hens; 4m pop-holes/100m area of house.
Enrichment on range	A minimum of 8m^2/1,000 birds of shade/shelter must be provided. Natural cover must account for at least 5% of the total range area. At least one area of facilities for dustbathing/ perching/ foraging per 2,000 hens.	Open-air areas shall be mainly covered in vegetation and must provide a minimum area of overhead shade of 4m^2 per 1,000 hens, in the form of natural cover (trees, shrubs, cover crops) or artificial screens. 5% natural cover on the range.
Bird sourcing and breed type	Pullets must be sourced from an RSPCA Assured-approved rearing unit	Birds must be sourced from organic registered holdings, or from non-organic flocks at up to 3 days old. Breed must be appropriate for the environment.
Beak trimming	Beaks can be trimmed at no older than 24 hours of age	Beak trimming only authorised by the competent authority on a case-by-case basis
Antibiotic use	In-feed antibiotics only for therapeutic reasons	Routine prophylaxis prohibited in absence of a known risk
Farm assurance	BEIC; RSPCA Assured.	BEIC; RSPCA Assured; Organic Farmers & Growers.

*Colonies are subdivisions of a flock into smaller groups using internal dividers in the house, preventing movement of hens between colonies.
˜The RSPCA Assured standard supersedes OF&G on nest allowance – 5 hens/nest in RSPCA Assured, 7 hens/nest in OF&G standard.
BEIC = British Egg Industry Council (Lion Code)

Table C Performance of 80 relatively efficient and inefficient laying hen flocks in England and Scotland determined using DEA, in terms of composite continuous criteria with lower and upper 95% confidence intervals.

Continuous variable	Value (lci / uci)
No. birds placed (thousands)˜	
Efficient	9.34 (7.78 - 10.9)
Inefficient	8.74 (7.48 - 10)
Total egg production (millions)	
Efficient	2.96 (2.42 - 3.49)
Inefficient	2.7 (2.31 - 3.09)
Egg production per hen day	
Efficient	0.79 (0.75 - 0.82)
Inefficient	0.8 (0.78 - 0.81)
No. egg seconds (thousands)˜	
Efficient	113.2 (75.95 - 150.45)
Inefficient	107.13 (66.08 - 148.18)
Percentage egg seconds (%)	
Efficient	3.74 (2.88 - 4.6)
Inefficient	3.71 (2.89 - 4.53)
Egg sales (£, thousands)^	
Efficient	232.16 (194.81 - 269.51)
Inefficient	209.91 (183.59 - 236.22)
Mean bird weight at depopulation (kg)	
Efficient	1.89 (1.86 - 1.92)
Inefficient	1.87 (1.83 - 1.91)
Biomass to factory (tonnes)^	
Efficient	16.4 (13.64 - 19.17)
Inefficient	14.34 (12.3 - 16.37)

Continuous variable	Value (lci / uci)
Energy use (MWh)˜	
Efficient	2.16 (1.43 - 2.9)
Inefficient	3.24 (2.45 - 4.03)
Total feed consumption (tonnes)˜	
Efficient	419.94 (338.14 - 501.75)
Inefficient	434.78 (372.52 - 497.04)
Feed conversion efficiency (g feed/egg)	
Efficient	141.87 (133.1 - 150.64)
Inefficient	162.89 (156.56 - 169.22)
Percentage bird days medicated (%)˜	
Efficient	0.43 (0.12 - 0.74)
Inefficient	0.67 (0.32 - 1.02)
Total mortality (%)	
Efficient	8.09 (6.09 - 10.09)
Inefficient	11.6 (10.05 - 13.16)

lci = lower 95% confidence interval | uci = upper 95% confidence interval | 'Efficient' flocks have a relative efficiency score = 1 and zero slacks; 'Inefficient' flocks have a relative efficiency score < 1 | ˜ = input variable in DEA | ^ = output variable in DEA | All variables relate to production stage only

Table D Final feather scores (at 70 weeks) of 80 laying hen flocks in England and Scotland, with the number and proportion of flocks attaining the maximum relative efficiency score determined using DEA, with lower and upper 95% confidence intervals.

Feather score~ (AssureWel protocol)	No. flocks	No. efficient flocks	Prop. efficient (lci/uci)
0 - No/minimal feather loss	12	9	0.75 (0.43 - 0.95)
1 - Slight feather loss	56	24	0.43 (0.3 - 0.57)
2 - Moderate feather loss	12	5	0.42 (0.15 - 0.72)

~ = input variable in DEA | Prop. efficient = proportion of flocks that are relatively efficient | lci = lower 95% confidence interval | uci = upper 95% confidence interval

DEA Mathematical Notation

Say $J = \{1,\ldots,\hat{j}\}$ denotes the group of $\hat{j}$ DMUs, where $R = \{1,\ldots, \hat{r}\}$ is the group of $\hat{r}$ output metrics, $I = \{1,\ldots, \hat{\imath}\}$ is the group of $\hat{\imath}$ input metrics, u_r and v_i are rth output and ith input weightings respectively, and y_{rj} and x_{ij} are rth output and ith input amounts of the jth DMU, respectively. The mathematic notation for calculating the DEA objective function, Technical Efficiency score (TE), using the CCR model of the jth DMU is summarised below (Cooper, Seiford and Tone, 2006).
Technical efficiency of DMU_j:

$$TE_j = \frac{u_{1j}\, y_{1j} + u_{2j}\, y_{2j} + \cdots + u_{\hat{r}j}\, y_{\hat{r}j}}{v_{1j}\, x_{1j} + v_{2j}\, x_{2j} + \cdots + v_{\hat{\imath}j}\, x_{\hat{\imath}j}} = \frac{\sum_{r=1}^{\hat{r}} u_{rj} y_{rj}}{\sum_{i=1}^{\hat{\imath}} v_{ij} x_{ij}}$$

TE_j = the DMU_j technical efficiency, where $j \in J$
u_{rj} = output y_r's weighting amount where $r \in R$ and $j \in J$
v_{ij} = input x_i's weighting amount where $i \in I$ and $j \in J$
y_{rj} = the output r amount produced by DMU j, and
x_{ij} = the resource input i amount applied by DMU j

Each DMU defines one set of output and input weights for the valuation of efficiency. Now let TE_o be the optimised TE_j. The optimised weights for the oth DMU, where $o \in J$, can be applied for any other jth DMU (where $j \in$ J), computing the relative technical efficiency TE_{oj}, for that set of weights. If $TE_{oj} = 1$ for $o = j$, then DMU_o is efficient, otherwise, the unit is inefficient.

To compute DMU_o optimal weights (those that maximise efficiency TE_o), one can solve the following non-linear programming model (Cooper, Seiford and Tone, 2006):

Maximise:

$$TE_o = \frac{\sum_{r=1}^{\hat{r}} u_{ro} y_{ro}}{\sum_{i=1}^{\hat{\imath}} v_{io} x_{io}}$$

Subject to:

$$\frac{\sum_{r=1}^{\hat{r}} u_{ro} y_{rj}}{\sum_{i=1}^{\hat{i}} v_{io} x_{ij}} \leq 1, \forall\, j \in J$$

$$u_{ro} \geq 0 \;\forall\, r \in R,\; v_{io} \geq 0, \forall\, i \in I.$$

Where:

y_{ro} = output r amount produced by DMU_o

x_{io} = resource input i amount which is applied by DMU_o

u_{ro} = weight allocated to output r calculated by DEA model, and

v_{io} represents the weight allocated to input i

The first constraint ensures that if the weights allocated to any DMU_j inputs or outputs are applied to the other DMU within group J, the efficiency score would be less than or equal to one. The second constraint sets the lower bound of the input and output weights for all DMUs to be non-negative i.e. ensuring the weights are greater than or equal to 0.

The model can be reformulated as a linear programming problem as follows (Cooper, Seiford and Tone, 2006):

$$\text{Maximise} \quad TE_o = \sum_{r=1}^{\hat{r}} u_{ro}\, y_{ro}$$

$$\text{Subject to:} \quad \sum_{r=1}^{\hat{r}} u_{ro}\, y_{rj} - \sum_{i=1}^{\hat{i}} v_{io}\, x_{ij} \leq 0, \forall\, j \in J$$

$$\sum_{i=1}^{\hat{i}} v_{io}\, x_{io} = 1$$

$$u_{ro} \geq 0 \;\forall\, r \in R, \qquad v_{io} \geq 0, \forall\, i \in I.$$

The model above is the CCR DEA model, which assumes that there is no significant relationship between the scale of operations and efficiency (Avkiran, 2001), implying that large flocks are just as efficient as small ones in converting inputs to output. Banker *et al.* (1984) suggested applying another model – BCC, assuming VRS, to derive 'pure technical efficiency' and from which scale efficiency can be derived. In this model, scale inefficient flocks are only compared to efficient flocks of a similar size. If there appears to be a discrepancy between technical efficiency and pure technical efficiency, then scale inefficiency occurs.

In order to adopt the VRS model, the CRS model described above can be modified by relaxing the constant returns to scale assumption. A measure of return to scale on the variables axis, c_o, for DMU_o, is added in the objective function and the first constraint. In an input-oriented framework, the BCC model can be described by the following linear programming multiplier equation (Huguenin, 2012):

$$Maximise: \quad TE_o = \sum_{r=1}^{\hat{r}} u_{ro} y_{ro} + c_o$$

$$subject\ to: \quad \sum_{i=1}^{\hat{i}} v_{io} x_{ij} - \sum_{r=1}^{\hat{r}} u_{ro} y_{rj} - c_o \geq 0 \qquad \forall\, j \in J$$

$$\sum_{i=1}^{\hat{i}} v_{io} x_{io} = 1$$

$$u_{ro} \geq 0\ \forall\, r \in R, \qquad v_{io} \geq 0, \forall\, i \in I.$$

Chapter 6

Interviewee recruitment letter and semi-structured interview questions

Dear Participant,

Thank you very much for agreeing to take part in a semi-structured interview as part of a project exploring opportunities to integrate regenerative agriculture principles into the University of Edinburgh's food supply chains. During the allocated interview slot, you will be asked the following questions. There is no need for any preparation for the interview and we will use the hour to explore your opinions as an individual on these themes.

Interview questions

A. **Our food system**

1. In your opinion, what should be the main outcomes of the global food system?
2. Which of these outcomes (your response to Q1) do you think our food system currently effectively delivers?
3. What frameworks and certifications are currently available to **farmers* to help them *produce* food products that deliver these outcomes (your response to Q1), and to **citizens* to help them *identify* these products?
4. What are the main barriers to **farmers* and **citizens* in *producing* and *consuming* food (respectively) that delivers these outcomes?
5. Have you heard of 'regenerative agriculture', and if so, what does it mean to you and what outcomes does it deliver?
6. For respondents that answered 'yes' to Q5: to your understanding, what frameworks and certifications are available for labelling food as 'regenerative'?

B. **University Food**

7. In your opinion, what should be the main outcomes of Edinburgh University's food services (including catered accommodation, campus catering and events)?
8. Which of these outcomes do you think Edinburgh University's catering services effectively delivers?
9. How do you think the University of Edinburgh could work with the supply chain to build a food system for the future?

**Questions were modified according to the key informant's area of work and expertise.*