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An economic lens to understanding antimicrobial resistance: disruptive cases to livestock and wastewater management in Australia

Bethany Cooper and Walter O. Okello[†]

The discovery of antimicrobial agents for the treatment of infectious diseases was one of the most significant events of the 20th century. Notwithstanding their importance, acquired resistance has become increasingly evident and this pattern has followed the introduction of each new antimicrobial agent. Antimicrobial resistance (AMR) has not only led to unwarranted mortality rates, but it presents as a major economic burden to societies. The alarming worldwide escalation in AMR poses a serious threat to public health and can cause major disruption globally. Whilst there has been progress in understanding AMR in the scientific literature, there is a dearth of knowledge that considers AMR from an economic perspective, especially as it relates to resource-based sectors. This paper uses two case studies to illustrate how an economic lens can improve understanding of the potential risks surrounding AMR and to identify the net welfare associated with specific interventions. We demonstrate the importance of economics when considering the impacts of AMR in the context of livestock and wastewater use in Australia and when quantifying the potential disruption to the economy. We also illustrate how economics can both highlight the magnitude of the risks from AMR but offer a way forward through cost-effective policy options.

Key words: antimicrobial resistance, antimicrobial risk, livestock management, risk-benefit analysis, wastewater management.

JEL classifications: Q1, Q5

1. Introduction

Antimicrobial resistance (AMR) is considered to be an urgent emerging threat to animal and human health (Prestinaci et al. 2015). Antimicrobials are medicines such as antibiotics, antifungals, antivirals and antiparasitics, used to prevent and treat infections in humans, plants and animals. Intensive use and overuse of these medicines, particularly antibiotics, for human and veterinary medicine, agriculture and animal farming has resulted in the widespread occurrence of antibiotic resistant bacteria in both clinical and natural environments (see, for instance, Ferri et al. 2017). AMR is recognised by the World Health Organisation as a major public health issue given

[†]Bethany Cooper (e-mail: bethany.cooper@unisa.edu.au) is a Senior Research Fellow at the University of South Australia, UniSA Business, GPO Box 2471, Adelaide, South Australia 5001, Australia. Walter Okello is a Research Scientist at CSIRO, Black Mountain Science and Innovation Park, P.O. Box 1700, Canberra, Australia.

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infections caused by antibiotic resistant bacteria are becoming increasingly challenging to treat. Currently, the emergence of antimicrobial resistance bacteria is outpacing the rate at which new antimicrobials are entering the market, and this imbalance is responsible for the growing public health concern that attends AMR (Mayor 2018). Lack of market incentives has also been sighted as a major reason for the slow pace of antimicrobial development (Nelson 2003). In agriculture, antimicrobials are used for the treatment and prevention of both livestock and crop diseases. Moreover, use of antibiotics in humans and livestock can result in environmental contamination with antibiotic residues, for example through manure and human waste, which eventually lead to resistant organisms in the environment. Animals and humans may acquire these resistant organisms through drinking water or being in contact with the soil (Woolhouse et al. 2015).

The consequence of AMR is the evolution of microorganisms that do not respond to standard treatments and therefore cause infections that cannot be treated or contained. It has been projected that AMR-related deaths will increase exponentially from the 700,000 deaths recorded in 2015 to 10 million from bacterial infections alone by 2050 (de Kraker et al. 2016). Without efficacious antimicrobial drugs, treatment of diseases will not be successful, leading to premature human mortalities, and broader impacts on food security and livelihoods, particularly by disrupting the production of animal sourced foods.

This paper looks specifically at ways of conceptualising the economic dimensions of AMR and uses two case studies to reflect on applications where economics can inform and improve decision-making in livestock and wastewater treatment sectors. The paper helps position AMR as a serious potential disruption and provides a foundation for future empirical investigations. The main contribution of this work is that it brings coherent economic insights into a field that has primarily been dominated by other disciplines and thus offers an alternative lens for contemplating the magnitude of the challenge at hand.

This paper itself is comprised of five main parts. The second section provides a simplified model for considering the key relationships that underpin the rise in AMR. Section three uses this framework to establish a typology for economic analyses in this field. Two case studies are then offered as a way of illustrating the role of economics in specific instances, namely using antibiotics in agriculture and by considering upgrades to wastewater treatment plants to service agriculture with reclaimed water supplies. Generalised lessons from these cases are discussed in section five along with considering a way forward.

2. An economic perspective on AMR

From an economic perspective, antimicrobials can be considered as a natural resource exploited by use of antibiotics resulting in an externality. AMR is deemed an externality because its impact is unlikely to be felt directly by the supplier or consumer of the antimicrobials, but it affects the overall welfare of the society (Kaier & Frank 2010). In one sense, AMR can be regarded as a pollutant that occurs due to treatment, and this can be captured using microeconomic evaluation. Although economic evaluation of AMR remains limited, particularly its burden in animal health, economists have conceptualised the problem as a negative externality with the potential of examining the trade-off between AMR and antimicrobial use (Lhermie et al. 2019; Rushton 2015).

Most studies on the economic burden of AMR have been based on quantification of the cost of AMR or antimicrobial use (Cosgrove & Carmeli 2003; Howard et al. 2001; Jit et al. 2020; Naylor et al. 2019; Oppong et al. 2016; Reynolds et al. 2014). However, the absence of a full evaluation of the burden of AMR points to the various challenges associated with its assessment (Coast et al. 1998). Antimicrobial resistance occurs in human, animal, and the environment domains, and it is still unclear how these interact to produce cascading effects. Moreover, the practice of modelling the costs and risks of AMR in the short, medium, and long terms is still significantly underdeveloped. Additional modelling challenges include limited data, how to address uncertainty and how to interpret the results (Knight et al. 2016). Further complications arise due to the diverse methods used to compute the economic impact of various types of diseases and associated AMR, and the different ways these are presented and communicated, for instance via cumulative cost as opposed to average expected annual loss (Dadgostar 2019). Also, macroeconomic assessment of AMR is rarely done, potentially resulting in governments underestimating its impact and underinvesting in mitigation (Smith et al. 2016). From a public health perspective, strategies, and interventions to tackle the risk of AMR are often naïve to economic issues (Coast et al. 1996).

One way to progress this issue is to consider AMR more broadly and the economic factors that might relate to it. This is done initially with the aid of Figure 1.

In Figure 1, the available antimicrobials for use by humans are presented as a stock. Here, we might conceptualise this as a form of capital that can be increased by scientific effort to identify and develop new antimicrobials that can be effective against emerging diseases (flow 1). The use of antimicrobials (flow 2) is considered to potentially generate some benefit that can be captured by humans in the form of reduced disease and thus enhanced production, in the broader sense (flow 3). Simultaneously, use of antimicrobials results in a level of antimicrobial resistance (flow 4) that further reduces the stock of useful antimicrobials (flow 5). What is clear from Figure 1 is that when presented as a highly simplified system it is possible to reach an equilibrium state provided that the flow of new strains of antimicrobials is adequate to replenish any rundown in the stock caused by use and AMR. In this simplified world, the problem reduces to understanding how to manage the flows in the system and the incentives that might sit behind them.

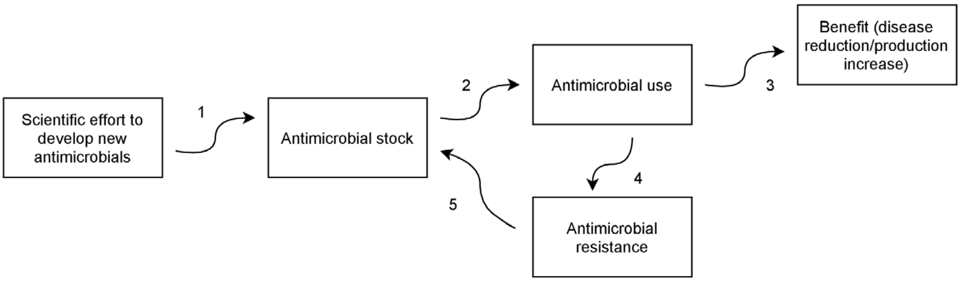

Figure 1 Simplified schematic of the AMR processes.

However, even to populate such a simplified model requires data that are not readily available for all forms of disease and antimicrobial use.

In addition, systems like those described in Figure 1 often imply a level of equilibrium that is not particularly representative of nature. As recent world events have attested, natural organisms do not always evolve and change at a constant rate such that major challenges to an equilibrium around antimicrobials could manifest with little warning. Nonetheless, as a starting point we systematically draw on the components of Figure 1 to help categorise our analysis.

3. A typology of economic analysis of AMR

Economic analysis can inform and manage many of the relationships in Figure 1, and whilst the economic literature on AMR can be traced for more than 30 years, it is far from comprehensive and cannot always provide the information required at a local scale. By using Figure 1, we propose a threefold typology for thinking about the extant AMR literature in economics. The first relates to the flow of new antimicrobials (depicted as flow 1) to replenish the stock of helpful antimicrobials. The second relates to the trade-offs inherent in use of antimicrobials and is captured by flows 2 to 5. The final category of analysis relates to a holistic view of all relationships depicted in Figure 1 and the related welfare costs.

In terms of this final holistic category, economic studies overwhelmingly have sought to highlight the magnitude of the AMR problem and monetise the cost of inaction. The seriousness of AMR is emphasised by the alarming predictions of a ‘postantibiotic’ era in which humans and animals will be vulnerable to bacterial infections just as it was in the era before the discovery of antibiotics (Brown 1994). Unfortunately, a postantibiotic world where minor injuries and common infections can result in death is a very real possibility for the 21st century (Michael et al. 2014). Globally, there have been multiple attempts to estimate the economic costs associated with AMR. For example, at the international level, it is estimated that AMR will reduce global gross domestic product (GDP) by up to 4 per cent and global livestock production by up to 7.5 per cent by 2050 (Jonas et al. 2017). In the United States, costs associated with AMR are estimated at US$20 billion a year and annual productivity losses are estimated at US$35 billion (Dadgostar 2019). In contrast, costs attributed to drug-resistant bacterial infections in Europe equate to Euros (EUR) 1.5 billion per annum (Dadgostar 2019).

Another strand of economic analysis sheds light on the relatively slow rate of replenishment of effective antimicrobials (i.e. flow 1 in Figure 1). The occurrence of AMR is exacerbated by the current lack of effective antimicrobials; presently, there are few antimicrobials under development due to lack of market incentives and research and development challenges (Renwick & Mossialos 2018). Furthermore, AMR can be considered as a public good in the sense that bacterial infections and AMR genes cannot be contained within national boundaries; globalisation through travel and trade results in quick spread of pathogens worldwide (Smith et al. 2003). In her 2006 review of the drug development pipeline, Larson (2007) noted that there are serious disincentives to the development of new antimicrobials including a decade-long development timeframe with only one in a thousand success rate and development costs of between US$ 800 million and US$ 1.7 billion. This is compounded by the relatively short patent time and the rate at which AMR occurs, making the investment returns poor. Overall, Larson (2007) recommends a range of measures to deal with these disincentives, including modifications to the taxation regime and measures to decrease the time and cost of drug development.

The bulk of economic analyses that attend the category of studies covering flows 2 to 5 in Figure 1 draw from four main economic methods. These include cost-benefit, cost-effectiveness, cost-minimisation and cost-utility analyses.

Cost-benefit analysis of antimicrobial use and resistance can be used to identify, quantify and evaluate the burden of AMR and the consequences associated with decision-making in monetary terms. In effect, this amounts to measuring the marginal costs of measures to reduce AMR (e.g. as a negative externality) compared to the marginal benefits. In contrast, cost-effectiveness analysis compares the monetary costs of an alternative with a single measure of effectiveness (Wilton et al. 2002). With both approaches, there is often significant uncertainty about the estimates and assumptions critical to the analyses can be opaque. Nonetheless, there is extensive recognition that the benefits associated with antimicrobial use frequently outweigh any adverse effects attributable to bacterial resistance or toxicity (Cosgrove & Carmeli 2003). Therefore, the key question should be whether patterns of use can be made more cost-effective or efficient rather than whether use is valuable (i.e. worth the cost) or cost-effective per se (Rice 1967).

Cost-minimisation analysis is an appropriate evaluation approach when the case for an intervention has been established and the actions or programmes under consideration are expected to have similar outcomes (Dakin & Wordsworth 2011; Robinson 1993). This is ostensibly a specific case of cost-effectiveness. Although there has been several debates on the merit of using cost-minimisation analysis, some authors argue that it is useful in instances where clinical consensus or existing research shows equal effectiveness, for example between drugs in the same pharmacological class (Drummond et al. 2005).

In contrast to cost-benefit and cost-minimisation, cost-utility analysis (CUA) integrates changes in the quality of life and changes in the quantity of life (mortality) into a health metric for comparison against the cost of intervention (see, for instance, Lake et al. 2014). The notion of health adjusted life years (HALYs) was established by health economists and the two most widely applied metrics of this form are the quality adjusted life year (QALY) and disability adjusted life year (DALY) (see, for instance, Lake et al. 2014). QALY calculations are commonly underpinned by preference-based health-related quality-of-life measures obtained from groups of patients or general population samples. Typically, the preference elicitation techniques are the time trade-off and the standard gamble choice-based approaches (Drummond et al. 2005). In the context of AMR, the issue of acute infection means that the derived trade-offs between quantity and quality of life might be unreliable, particularly if the state of ill-health is perceived as transient (Gold et al. 2002; Holmes & Hughes 2019).

DALY provides an estimate of the burden of disease that can be used for health prioritisation at the national or global level. DALY differs from QALY by seeking to capture the healthy years foregone in the absence of an intervention; this includes any reduction in life and loss through disability. The aim of health interventions is to reduce DALY and increase QALY. Although the application of CUA has been limited in the context of AMR, it has been used to estimate the burden of AMR in Europe and determine cost savings from using different types of antimicrobials (Grotle et al. 2020).

In agriculture, attempts have been made to include Animal Loss Equivalent, as a DALY equivalent when assessing diseases that pass from animals to humans and vice versa (zoonoses) (Okello et al. 2018; Torgerson et al. 2018). QALY and DALY are particularly useful when thinking about the benefits of reducing AMR from a public good perspective. That is, slowing AMR can potentially lead to major improvements in human health and this is generally regarded as a public good, even if it is potentially achieved through privately designed incentives.

Most decisions in an agriculture production context (i.e. flows 2–5 in Figure 1) are concerned with how much of a service should be provided. For example, should samples collected from sick animals be taken for further analysis to detect AMR? How many sick animals presenting with a particular disease should be tested or have specialised treatment? In other resource-based industries, such as wastewater treatment, the concern would be whether to expand or upgrade the facility to excise contaminants such as microorganisms and AMR genes as well as limit the generation of AMR (Guo et al. 2017). All these decisions require a focus on marginal costs, that is the change in total costs due to marginal change in activity (Rushton et al. 1999). However, some of the decision-making processes may be complex, risky and uncertain and the benefits uncertain and potentially split between private individuals and the wider public. Economic approaches that can be used for decision-making under risk and uncertainty thus have much to offer here, including real options and discounting utility modelling techniques (Baucells & Heukamp 2012; Drury 1992; Janney & Dess 2004; Koopmans et al. 1964).

Apart from the traditional economic evaluation methods, risk analysis can be applied to understand the impact of AMR (Opatowski et al. 2020). Risk analysis has proven a useful tool in examining the level of threat to human health associated with AMR spread from livestock, as well as from the environment (Anderson et al. 2001; Cox 2005; O'Flaherty et al. 2019). Risk analysis has also been used to predict the impact of banning antimicrobial use in agriculture (see, e.g., Cox & Popken 2004).

4. Building a case for more targeted economic research – the case of agriculture and wastewater reuse

4.1 Case 1: Agriculture in Australia

In agriculture, AMR is usually regarded as a social cost (Anomaly 2009; Innes et al. 2020). However, it does affect livestock production and there are concerns that AMR could ultimately disrupt global trading systems and the world economy (George 2019). Imported food is already being tested to check for levels of antimicrobial residue and pesticides as part of the World Trade Organization no-discriminatory framework, which includes public health priorities, technical barriers to trade and sanitary and phytosanitary agreements. Additionally, consumer pressure on antimicrobial use may result in further disruption of trade (George 2019).

Globally, there has been a considerable debate on the need to reduce use of antimicrobials in agriculture. On the one hand, antimicrobials are considered to play a major role in enhancing productivity; however, there is also a long-term, but often unknown, risk to food production from overusing some antimicrobials in agriculture, including antibiotics. In Australia, studies show that the occurrence of AMR in animal production is currently relatively low (Abraham et al. 2014; Al-Habsi et al. 2018; Abraham et al. 2019; Barlow et al. 2015; Sahibzada et al. 2020; Wallace et al. 2020). The low level of AMR in livestock in Australia is likely due to the relatively strict regulation of antimicrobials in food animals and high biosecurity standards (Barlow et al. 2015). The relatively extensive agricultural systems in some parts of Australia also likely play a part in this result. However, the complex nature of AMR, trends towards increased intensity of production systems and the potential for AMR to cause widespread disruption to the economy warrant ongoing review (Barlow et al. 2017).

Economic evaluation of livestock diseases is largely based on cost-benefit analysis and gross cost estimates. Costs associated with animal disease control have two components, namely losses and expenditure. Losses are potential benefits not realised due to the occurrence of disease or other conditions, for example discarding milk due to mastitis. Expenditures (both preventative and treatment) are resources that are allocated to unexpected uses, such as response to a disease outbreak or veterinary services. Consequently, the economic cost of animal disease (C) is usually regarded as the sum of losses (L) and expenditures (E), as in Equation (1):

$$C = L + E \tag{1}$$

This gives rise to a loss avoidance function in the form of Equation (2)

$$L = A - f(E), \tag{2}$$

where L is avoided losses, A the loss incurred if there is no control of a particular disease, and E the expenditure at the farm level (McInerney et al. 1992). This function can be extended to include public and indirect expenses borne by the society (S), such as research and development and project costs as part of an intervention and thus

$$L = A - f(E,\ S) \tag{3}$$

Loss avoidance is the tendency to avoid choices that will certainty yield negative payoffs in favour of alternatives that could yield positive payoffs, and this has been used to derive the loss-expenditure frontier (McInerney et al. 1992; Cachon and Camerer 1996). Given AMR is not a diseases per se, it is likely to cause excess losses and expenditure relative to the total cost of a disease. At the farm level, farmers will respond to the occurrence of animal diseases, incurring different types of expenses and losses.

Here, we take mastitis as an illustrative example to show the process for identifying and quantifying key costs related to AMR. In Australia for example, the prevalence of subclinical mastitis (an inapparent infection) ranges between 29 and 50 per cent in dairy herds depending on the pathogen. In the United States, the costs of mastitis to the dairy industry were estimated at US$ 60 million a year (Ghadersohi et al. 1999; Munro et al. 1984; Plozza et al. 2011), and to our knowledge, no new published data on these costs have been generated. Subclinical mastitis usually results in more apparent cases of clinical mastitis (Cobirka et al. 2020). In Figure 2, a simple decision tree adapted from Steeneveld et al. (2011) is used to show progression of clinical mastitis with treatment using antibiotics.

In Figure 2, complete cure means bacteriological and clinical cure. Clinical cure comprises no bacteriological cure, while 'no cure' relates to instances where there is no bacteriological or clinical cure. An extended treatment is

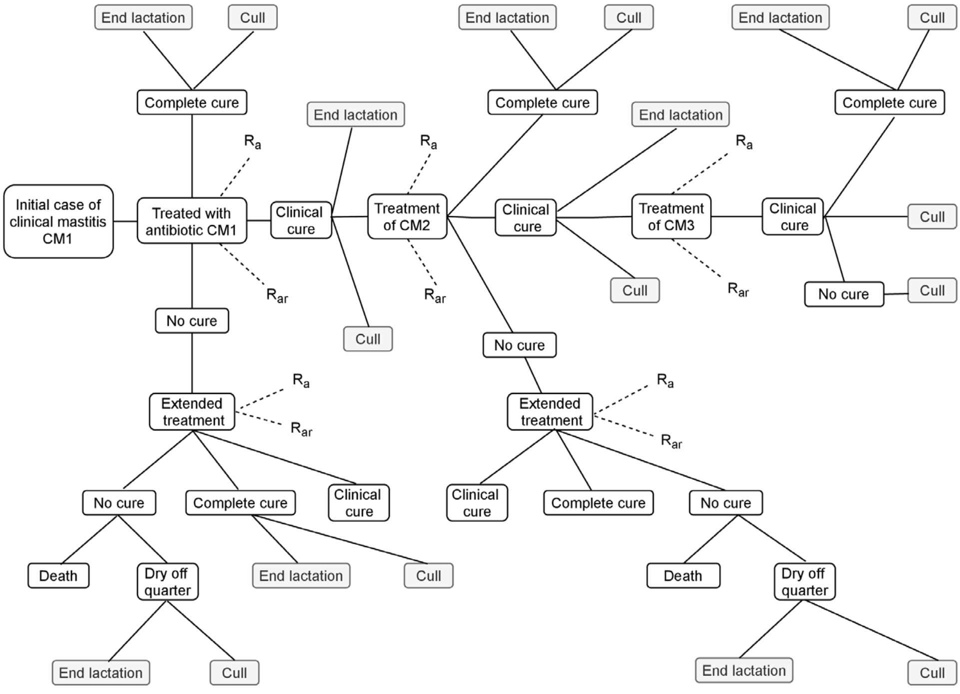

Figure 2 Schematic model representing treatment of clinical mastitis with antibiotics, adapted from Steeneveld et al. (2011).

taken as a repeat of a previous treatment, while R_r captures the risk of AMR occurrence and R_{ar} symbolises the risk of antibiotic residue in milk. CM1 defines the initial case of clinical mastitis and CM2 and CM3 relate to the second and third occurrence of mastitis, respectively.

Here, we have cows being treated with antibiotics, and rates of antibiotic effectiveness (i.e. in the form of cure rates) translating to final outcomes. Although not presented in Figure 2, there is a possibility that some farmers will not treat mastitis, and this can be included to evaluate a do-nothing scenario. Additionally, it is likely that no cure after extended treatment with antibiotic will result in death. Based on loss avoidance, it is logical that most farmers will treat their cows for mastitis. However, the effectiveness of the antibiotic used will determine whether a dairy cow is bacteriologically and clinically cured indicating the importance of cure rate in resolving the problem of mastitis. Also, the use of antibiotics will likely result in the occurrence of AMR over time and subsequently in treatment failure.

Use of antibiotics also results in the presence of antibiotic residue and discarding of milk is likely to reduce curate rate even further. From Figure 2, it can be observed that mastitis can have repeated episodes depending on cure rate (Cha et al. 2013). The ultimate result of repeated episodes is future decrease in the effectiveness of antibiotics due to AMR, and this in turn results in: (1) increased losses, that is culling, replacement of cows, discarding milk due to antibiotic residue, reduction in milk production and mortality; and (2) increased expenditure, for example veterinary services, diagnostic tests and fines paid due to antibiotic residue at different time periods with different probabilities.

Time and probability are thus key attributes influencing whether repeated use of antibiotics (because of repeated episodes of mastitis) may result in adverse outcomes. In this situation, a decision-maker, for example a farmer or policymaker, faces a trade-off between an immediate and/or certain reward (i.e. present use of antibiotics will immediately and certainly cure mastitis, at least at a given rate) and a delayed or uncertain reward in the future (i.e. delayed response to treatment and uncertainty whether the antibiotic will be effective in the future). Antibiotic effectiveness in the mastitis example can be viewed as a utility and potentially assessed using discounting utility model enabling discounting of the future (Rambaud and Pérez 2020). Here, antibiotic effectiveness within each time periods is additively separable, so we can write utility in period t as

$$u(x_t,\ y_t) \tag{4}$$

where x and y are the variables that impact antibiotic effectiveness in period t and u is the felicity function. Typically, u is concave so that

$$u'(x) > 0 \tag{5}$$

and

$$u''(x) < 0 \tag{6}$$

Future antibiotic effectiveness in treating mastitis can be discounted at a constant rate p, which is the rate of time preference, which is sometimes written as part of a discount factor

$$\beta = \frac{1}{1+p} \tag{7}$$

The total antibiotic effectiveness, U, over all time periods for a flow of $\{x_t,\ y_t\}\frac{T}{t=0}$, where T is the end of the time period, is thus given by

$$U(x_t,\ y_t \ldots x_T,\ y_T) = \sum_{t=0}^{T} \left(\frac{1}{1+p}\right)^t u(x_t,\ y_t) \tag{8}$$

Despite the apparent elegance of deploying relatively standard economic approaches to the problem at hand, there are no clear instances in the literature where this has been done, let alone in an Australian context. This represents both a major opportunity for economics to be applied to help shape policy decisions and a serious gap in the armory of policy decision-makers. As standards on the surveillance of exported animal product increase, understanding the economics of AMR at an industry scale will be increasing useful.

4.2 Case 2: Wastewater reuse

AMR in agriculture is only one dimension of the problem. Wastewater treatment plants (WWTPs) also act as significant reservoirs of antimicrobial resistance. Globally, antimicrobial resistant bacteria and resistant genes have been extensively detected in WWTPs, and the removal of AMR through most existing wastewater treatment processes is largely ineffective (Ben et al. 2017; Bruchmann et al. 2013; Du et al. 2015). In addition, WWTPs may provide a conducive environment for the spread of AMR, where the wide diversity and high abundance of bacteria facilitate gene transfer (Barancheshme & Munir 2018). Subsequently, bacteria that contain resistant genes are not effectively eliminated and sometimes even increase inside the biological components of WWTPs (Ben et al. 2017; Zanotto et al. 2016). Although disinfection processes are vital to advance effluent biosecurity, disinfection with chlorine or ultraviolet light cannot guarantee the removal of antimicrobial resistant genes (Sharma et al. 2019). Consequently, there is a risk that antimicrobial resistance is being distributed by discharge or reuse of WWTP effluents in receiving environments, such as rivers and wastewater-irrigated soils (Ben et al. 2017; Makowska et al. 2016). In this context, WWTPs and their related technology can provide a feedback loop into agriculture, particularly if agricultural producers opt to employ reclaimed water, as is being widely encouraged in countries facing disruptions to rainfed agriculture, like Australia (Hamilton et al. 2005).

In Australia, wastewater treatment includes an array of physical, biological and chemical processes and the most common methods include disinfection and solid removal. Success is largely based on meeting health and sanitary requirements such as reduction in the number of human pathogens in water sources. As a general rule, these criteria do not specifically address AMR. The ‘cleaned’ water (effluent) is generally returned to rivers and oceans but the prospect of substantially more episodic rainfall variability due to climate change, has increased interest in reclaiming wastewater for irrigation in food production. Reclaiming wastewater offers great promise to users who require consistent supply, and the cost of some treatment technologies that were previously very expensive has also been decreasing as adoption rises (Figoli & Criscuoli 2017). One of the desired features of the newer technologies is that they have capacity to remove bacteria and AMR genes from wastewater. For instance, equipping wastewater treatment plants with systems able to break down pharmaceuticals is one way to reduce the impact of AMR (Ejeian et al. 2018). Other experimental evidence is available to show that feasible options are on hand to completely remove antimicrobial resistant bacteria and genes as well as mobile genetic elements that contribute to the development of resistant bacteria (Krzeminski et al. 2020). Clearly, these approaches increase the potential uses to which reclaimed water can be applied, but the relative benefits and costs of advanced treatments like membrane bioreactors, ozone and activated coal are not well understood.

In the current Australian legislative setting, upgrading WWTPs is most likely to occur in response to meet public health or environmental criteria imposed by the relevant state health department (such as pathogen removal), but simultaneously water utilities are also keen to understand how reclaimed water might be marketed to help shoulder costs.

Upgrading of WWTPs requires modification of existing structures, which necessarily carries a cost. There are also likely flow-on effects in terms of insurance, property tax, salaries along with maintenance, energy costs and reagents. Fouling is also a major drawback of using membrane technology imposing additional maintenance activities (Amjad 1997; Hamza et al. 1997); however, the recovery of nitrogen and phosphorous, for example through struvite precipitation, ion exchange and stripping, also represents additional value (Beckinghausen et al. 2020).

The economic benefit of wastewater reuse in agriculture is linked to the value of crop irrigation. Irrigation can improve crop yields and decrease yield variations caused by irregular rainfall. A key issue is thus the extent to which irrigators might privately benefit from access to high-quality, noninterruptible water supplies from WWTP and the extent to which they are willing to meet the costs related to WWTP upgrades.

If we assume that removal of antimicrobials, antibiotic genes, and salinity and recovery of nitrogen and phosphorous among other components represents the preferred solution to meet environmental, public health and financial obligations, the key question is understanding at what point private agricultural businesses will be willing to pay for the recovered resources. The case of the recently developed Northern Adelaide Irrigation Scheme (NAIS) provides some insights in this regard. In this instance, a major development was supported by State and Federal governments to deliver 12 Gigalitres of reclaimed water for agricultural use in the first phase of the scheme. Representing an investment of over A$155 million, the project aimed to foster a modern agricultural and food precinct to the north of the city comprised of 300 hectares of high-technology horticulture, and 2,700 ha of advanced agri-food production (DPIR 2020). The reclaimed water already available is delivered under contract with users expected to pay an upfront capital contribution of around A$3,000 per megalitre along with access (availability) and consumption charges. The combined availability and consumption charges vary with the quality of the water on offer, with higher quality water selling for approximately A$1,000 per megalitre and lower grade water available for around half that amount. It is worth noting that this higher quality water does not assure the removal of AMR and additional costs would be required to take the treatment plant to this next level of technical sophistication. While a cursory analysis of the asking prices to participate in the scheme sit below the reservation prices to sustain most local enterprises, uptake from the scheme has been modest. Arguably, the prospect of agricultural users willingly paying even more for higher quality, zero-AMR water is very remote, implying actions on this front will likely need wider public support.

In addition to supporting agricultural production, the current scheme and any future upgrade offers several environmental benefits, including reduced discharge to surrounding waters and the environment. Regardless of these benefits and the mounting pressure on agriculturalists to gain surety of water supplies, few landholders had opted into the scheme even after several years of lobbying by the proponents (see Advertiser 2017). This raises empirical questions about the extent to which the public good attributes of reducing AMR in the environment might be used to rationalise public support for higher quality reuse being made available to agriculturalists. Unfortunately, and as is the case for many AMR-related questions in agriculture, there is a dearth of existing Australian cases on which to draw.

5. Lessons, ways forward and concluding remarks

The two case studies show that it is eminently feasible to apply economics to enhance our decision-making around the treatment of AMR and its related risks. The decisions required are circumscribed by uncertainty, trade-offs are likely to occur over time and space, and a mix of public and private incentives will likely drive the response. None of these complicating factors are insurmountable and there are ample cases in related fields where economic analysis has been used to shed light on alternatives. So why is the economic analysis of AMR lagging?

The holistic international studies on AMR show its potential to cause major disruption and welfare loss, but there is a general lack of urgency to fully understand the challenges within specific contexts and to enumerate economically efficient responses. This raises the risk that an unexpected rise in AMR could lead to ad hoc mandated changes to trade and food industry supply chains, due partly to a lack of understanding of the value of alternative options and their related timeframes.

As highlighted in both cases, there is ample scientific background to trace the impacts of AMR in multiple settings. Similarly, there are technical solutions at hand that can reduce AMR in the environment and methods to extend the useful life of existing effective antimicrobials. However, as with other well-known but wicked problems, the political will for action is mixed. In the Australian case, there is also the likely perception that AMR is not as pressing as other forces that bear on agriculture, and thus, the need for immediate action to match other jurisdictions, like Europe, is downgraded.

Standing in contrast to this approach is the stark reality that Australian agriculture is predominantly export focused and market access is an ongoing threat to many industries. Without a significant and sustained effort by the applied economics community to raise the importance of the economics of AMR, these risks seem set to increase.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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