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Romain Espinosa[a]

Damian Tago[b]

Nicolas Treich[c]

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Abstract: Most infectious diseases in humans originate from animals. In this paper, we explore the role of animal farming and meat consumption in the emergence and amplification of infectious diseases. First, we discuss how meat production increases epidemic risks, either directly through increased contact with wild and farmed animals or indirectly through its impact on the environment (e.g., biodiversity loss, water use, climate change). Traditional food systems such as bushmeat and backyard farming increase the risks of disease transmission from wild animals, while intensive farming amplifies the impact of the disease due to the high density, genetic proximity, increased immunodeficiency, and live transport of farmed animals. Second, we describe the various direct and indirect costs of animal-based infectious diseases, and in particular, how these diseases can negatively impact the economy and the environment. Last, we discuss policies to reduce the social costs of infectious diseases. While existing regulatory frameworks such as the "One Health" approach focus on increasing farms' biosecurity and emergency preparedness, we emphasize the need to better align stakeholders' incentives and to reduce meat consumption. We discuss in particular the implementation of a "zoonotic" Pigouvian tax, and innovations such as insect-based food or cultured meat.

Keywords: Infectious diseases, meat production, meat consumption, biodiversity, prevention, intensive farming, regulation, taxation.

JEL codes: I18, Q18, Q57

Authors' affiliations: a: CNRS, CREM, Rennes, France; b: Emergency Centre for Transboundary Animal Diseases, Food and Agriculture Organization of the UN, Regional Office for Asia and the Pacific, Bangkok, Thailand; c: Toulouse School of Economics, INRAE, Toulouse, France.

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I) Introduction

The COVID-19 pandemic invites us to reflect on infectious disease risk prevention policies. If the current emergency is to mitigate the impacts of this pandemic and address the induced economic and social damages, we must collectively improve our capacity to prevent the future risks of infectious disease outbreaks. In particular, we must better understand the mechanisms that increase the risk of the emergence of infectious diseases and their severity, and properly assess the role of economic development, globalization, trade, urbanization and population growth. In this paper, our objective is to specifically examine the role of animal farming and animal consumption in relation to epidemic outbreaks.

About 75% of emerging infectious diseases are zoonotic; that is, they are transmissible diseases between humans and animals. Zoonoses cause approximately one billion cases of illness in people and millions of deaths every year (Karesh et al., 2012). Many of these diseases have emerged only recently, such as the avian influenza H1N1, severe acute respiratory syndrome (SARS), West Nile virus, Nipah virus, and bovine spongiform encephalopathy (BSE). Additionally, endemic zoonotic diseases such as rabies and brucellosis continue unabated in many countries. The recent synthesis of the literature by Rohr et al. (2019) finds that, *“since 1940, agricultural drivers were associated with >25% of all — and >50% of zoonotic — infectious diseases that emerged in humans, proportions that will likely increase as agriculture expands and intensifies*”.

While traditional animal food sources such as bushmeat and backyard farming increase the risks of disease spillover from wild animals, intensive animal farming creates conditions for the emergence and amplification of epidemics because of the physical and genetic proximity of the billions of animals, often in frail health, that are raised indoors every year (Coker et al., 2011). Moreover, animal farming likely contributes indirectly to the spread of pathogens from wild animals due to deforestation and biodiversity loss associated with the expansion of agricultural land use (Civitello et al., 2015). These threats may expand under global warming conditions, to which animal farming also contributes. Industrial animal farming is also an incubator for antimicrobial resistance, given that most antibiotics used worldwide are for farmed animals (O’Neill, 2015), often for prophylactic use.

The social costs induced by animal infectious diseases can be significant, as the COVID-19 pandemic shows. They include both direct human and animal health costs, but also the indirect economic costs of business activity reduction and the associated environmental impacts during and after an epidemic event, as well as the cost of preventive measures, such as farm and wild animal culling. Additionally, they include various other indirect costs linked to monitoring and preparedness measures. Moreover, these costs, as we will demonstrate, are largely supported by the public sector. They also tend to disproportionately hurt the poor; that is, those who lack insurance and safety nets and cannot adopt preventive measures without compromising their livelihoods.

The current COVID-19 pandemic is not an exogenous event. Its emergence, spread and severity depends on human actions. Even though this event is very specific and unprecedented, it should not be seen as anomalous and unexpected, or simply attributed to “bad luck”. Between 2011 and 2018, the WHO tracked 1,483 epidemic events in 172 countries (GPMB, 2019), and six public health emergencies of international concern have been declared since 2009. Hence, meat production imposes great risks to our societies and the current prevention systems seem to have largely reached their limits. From this perspective, we are probably seeing an unusual policy window opening in response to the COVID-19 pandemic, as regulators as well as private investors are being pressured to consider how best to prevent the next crisis (FAIRR, 2020).

Given the global threats posed by infectious diseases, it is time to reexamine our regulatory framework, and broadly address health risks at the human–animal–environment interface consistent with the “One Health” approach. We must reduce our exposure to the animals from which we can get infected, and thus complement the current risk management approach by means of improved regulation of the production of meat and a reduction of its consumption in developed countries. As a result, the risk of zoonotic disease should be reduced, while also reducing other externalities (e.g., climate change, air and water pollution). Economics can help to inform and design this broader regulatory framework by better aligning the incentives of food producers with the common good, and by using appropriate fiscal, informational and behavioral instruments to foster dietary changes and innovations.

The remainder of the paper is organized as follows. First, we discuss how meat production and consumption increases the risks of infectious diseases. Second, we discuss the costs associated with animal-based infectious diseases. Last, we discuss the policies that could be implemented in order to reduce the costs related to animal-based infectious diseases.

II) The role of animal farming and meat consumption

The production and the consumption of animal-based products contributes to an increase in the risks of infectious diseases (see Figure 1). The consumption of wild animals (or bushmeat) is an important driver of new zoonoses. Wild animals are indeed important reservoirs of infectious diseases, and most of the zoonotic pathogens originate from wildlife. Animal farming plays a major role in the emergence and the spread of zoonotic pathogens, as numerous common infectious diseases reach humans through domestic animals (e.g., smallpox, tuberculosis; Wolfe et al., 2007). Backyard farming involves important risks in its exposure to wild animals through means other than commercial production. Intensive farming may reduce the likelihood of pathogen introduction through biosecurity intervention but significantly increases the risks of amplification, spread and the mutation of pathogens once they enter farming facilities. In addition, the deforestation associated with the increased production of meat deteriorates natural habitats and biodiversity, which can indirectly increase epidemic events.

1) Bushmeat

Scientists estimate that a large share (72%) of zoonotic infections originate from wildlife (Jones et al., 2008), and increased contact with wild animals increases the risks of human exposure. Among the human-wildlife interactions, the hunting of wild animals, their butchering and the consumption of their flesh are important sources of contamination (Wolfe et al., 2005). Ebola is a well-known example of a zoonotic disease resulting from such activities, however, HIV (chimpanzees), anthrax (ungulates) and Simian foamy viruses (gorilla) also originate from wildlife hunting and eating. The use of wild bats as food also generates important problems (Kamins et al., 2015) as bats are unique in their propensity to host zoonotic viruses (Luis et al., 2013). The consumption and trade of bushmeat is especially important in developing countries, such as Botswana (Alexander et al., 2012), Ghana (Kamins et al., 2015), Cameroon (Wolfe et al., 2005), Sierra Leone (Subramanian, 2013), and China (Zhou et al., 2014).

The use of bushmeat generates risks at several stages. The tracking, trapping, and slaying of wild animals increases the likelihood of exposure to pathogens, since hunters are in close contact with the animals and zoonoses can be transmitted by scratches or bites. Butchering is also a major source of zoonotic transmission as bodily fluids, bodily tissue and excrement further spread the pathogens. Local populations using bushmeat seem well aware of the associated disease risks but only a small minority take precautionary measures (LeBreton et al., 2006). Further evidence suggests that women involved in these activities might be at higher risk as they are more frequently involved in the butchering process (Subramanian, 2013). The spread of the pathogenic agents from bushmeat can be further increased by illegal trade to more developed countries (Chaber et al., 2010; Smith et al., 2012). The popularity of consuming wild animals has contributed to the emergence of wildlife farming. Some studies claim that farming undomesticated animals that are usually hunted can help protect these species from extinction (Nogueira and Nogueira-Filho, 2011). The increased supply is indeed expected to reduce the price of hunted animals, and, thus, reduce the attractiveness of hunting them (Damania and Bulte, 2007). However, wildlife farming shows the important risks of infectious diseases as wild species that are bred in those farms are important hosts of pathogens. These animals are mostly sold in live animals or so-called wet markets.

2) Backyard farming

Backyard farming, also called family farming, is characterized as a low input/low output system and is mainly (but not only) prevalent in developing countries (FAO, 2020a). Backyard production systems (BPS) are a key element of food security in the developing countries that lack easy access to plant-based proteins (FAO, 2020b). In these countries, the consumption of animal-based proteins can lead to better nutrition, which can bolster the immune system in fighting infections (Rohr et al., 2019). Previous findings have shown, for instance, that undernourishment is a risk factor for tuberculosis, but can, in some cases, mitigate hyperinflammatory diseases or parasitic proliferation. In addition, BPS have been the source of multiple epidemic outbreaks, even though the data suggest that it may be associated with fewer risks of outbreaks than those in intensified farming (Otte et al., 2007; La Sala, 2019). One reason for the relatively lower risks of epidemic outbreaks is that the current breeds of animals in BPS have survived previous epidemics (through natural selection) (Minga et al., 2004; Conan et al., 2012).

Nonetheless, the risks of epidemic outbreaks in BPS are significant and mainly result from the increased contact between domestic and wild animals (e.g., Henning, 2011; Wang et al., 2013). Although backyard farmed animals live in (or very close to) the family house, they are less likely to be monitored and handled than pets that live in the house, leading to lower disease detection rates (Whitehead et al., 2014). Low levels of biosecurity and poor levels of hygiene (e.g., the presence of rodents, lack of cleaning regimes/equipment, no quarantine) may also increase the risks of infectious disease transmission (Coan et al., 2012). Moreover, BPS tend to make limited use of preventive medicines such as vaccines, which also leads to an increase in the risk of infection. However, the sanitary risks associated with BPS are heterogeneous: while most backyard farms have relatively low levels of biosecurity (e.g., Hamilton-West et al., 2012), some countries achieve high vaccination rates (e.g., Kamakawa et al., 2006).

3) Intensive Farming

Since the end of the Second World War, animal farming has undergone a transition from traditional small-scale farming methods to large-scale industrial operations (Graham et al., 2008). Developed countries, such as the USA or member states of the European Union, initiated those changes to respond to the growing demand in the consumption of animal-based products, and many developing countries with an increasing level of income, such as China, are following the same path (Zheng, 2013). These intensive farming methods have led to the emergence of new agricultural models, in which hundreds or thousands of animals such as pigs and poultry, often of a single breed, are farmed in high-density closed facilities. In these intensive farms, animals have no outdoor access, remain in highly controlled and confined facilities, receive large doses of antimicrobials (Van Boeckel et al., 2015), and eat specific feed that replaces the foraging crops normally eaten (Graham et al., 2008). The intensification of animal husbandry has had the beneficial consequence of reducing the level of contact between farmed and wild animals. It has also reduced the likelihood that farmed animals come into contact with pathogens, and has thus helped to reduce disease risks. However, at least four negative consequences have resulted from this intensification that are likely to outweigh this benefit: (i) the increased scale of disease impact, (ii) the immunosuppression of intensively farmed animals, (iii) the risks of contamination for animals and humans living outside of farms, and (iv) the risks associated with transportation.

Intensified farming has probably reduced the likelihood of the first contamination of farmed animals (entry risk), but has worsened the consequences of contamination within the farm (exposure risk): contamination events may have become less frequent but are far more severe. Dhingra. et al. (2018) show for instance that intensified farming systems are responsible for a small share of the reassortments of avian influenzas (small or moderate risks) but concentrate most of the conversion events from low pathogenic to highly pathogenic viruses (high risks). Several factors contribute to this phenomenon. First, the high animal density in intensive farms leads to a greater spread of pathogens within the facilities (Graham et al., 2008; Cutler et al., 2010). Thousands of animals can be infected within a few days. Second, the selection of the most profitable species of farmed animals in intensive farms has led to a high level of genetic similarity. The genetic similarity among farmed animals facilitates the spread of the pathogens as all animals within the farms are immunologically naïve hosts, increasing the chance of catastrophic epidemics (Springbett et al., 2013; Drew, 2011). In addition, genetic proximity and high density together offer ideal circumstances for the pathogens to mutate and evolve, which increases the risks of a mutation that is transmissible to humans (i.e., zoonoses). To avoid the risk of human contamination, as well as a spread to other facilities, intensive farms in high risk zones usually cull all animals once a case has been detected. For instance, during the H5N1 influenza epidemic, more than 230 million birds were killed by the disease or culled in counter-epizootic measures (Karesh et al., 2012). To further minimize the risks, wild animals in the surroundings are also often culled (as was the case for wild boars with the African Swine Fever or for badgers with bovine tuberculosis). The killing of all animals in and around the farm prevents natural selection (that is, the survival of resistant breeds), and thus reduces their chance of adaptation to the pathogens in the future.

Animals bred in intensive farms are raised and transported in stressful conditions that weaken their immune systems, and, in turn, increase the risks of infection (El-Lethey et al., 2003; Rostagno, 2009). To prevent the contamination of immunodeficient animals, intensive farms make intensive use of preventive antimicrobial drugs (*Prophylaxis*). The drug intakes increase disease risks in three ways. First, the intensive use of antimicrobials can suppress the immune system of farmed animals, which can lead to a vicious circle (Yang et al., 2017). Second, they facilitate the emergence of antimicrobial-resistant pathogenic strains (Gorbach, 2001; Laxminarayan et al., 2013; Rohr et al., 2019). As stressed in the previous paragraph, intensive farms are ideal environments in which pathogens can mutate. The high number of potential hosts treated with antibiotics increases the chance of the mutation of the pathogen into a strain that is resistant to antimicrobial drugs. Third, an important share of antimicrobials end up in the environment, either directly, or through the water system, which further increases the risk of the development of resistant strains in wildlife and humans (O'Neill, 2015).

The third type of externality due to the intensification of animal husbandry is the associated risk for domestic and wild animals that live in close proximity to farming facilities and also to the humans who work there. The risks of contamination of nearby animals mainly result from two sources. The first source of contamination is ventilation. In case of infection in a farm, the air coming out of the facilities via the ventilation systems carries the pathogens to the farm's surrounding neighborhood by means of wind and surface water transportation (Otter et al., 2007). Contamination within a facility is therefore likely to spread to animals outside of the facility, which, in turn, increases the risk of propagation. A second source of spillover is the indirect contamination of non-farmed animals via animal waste, including dead animals and fecal matter. Non-farmed animals can either come into contact with the waste when it is not stored in a confined place or when biosolids are spread on the land and can contaminate water (Graham et al., 2008; Jones et al., 2013). Last, the intensification of animal husbandry increases the risks for humans (Graham et al., 2008). Intensive farms require various people to be involved in the farming process (veterinarians, stock personnel, slaughterhouse workers, transportation teams), and neighbors of the facilities are also exposed to animal waste and ventilation risks.

Fourth, unlike backyard farming, where the produce is usually eaten at the local level, intensive farming produce is largely destined for exportation. With the reduction in transportation costs and the intensification of the livestock sector, the world trade in livestock and livestock products have increased substantially (Naylor et al., 2005). In 2017, approximately two billion animals were transported on ships (Levitt, 2020). The journeys usually take place in very poor conditions and can last up to several weeks (Schuck Paim and Alonso, 2020). During these journeys, animals live in close proximity, are immunosuppressed, and are in constant contact with other animals and with their own waste. The long-distance transportation of live animals and livestock products increases the risk and speed of a disease spreading (Di Nardo et al., 2011), such as with the African Swine Fever in China (Wang et al., 2018) and influenza A globally (Nelson et al., 2015).

4) Extensive or semi-intensive farming

Backyard and intensive farming represent two extreme models of meat production, and a variety of farms range between these two production methods (extensive farming, semi-intensive farming, free-range farms, pastures, etc.). These intermediary production systems play an important role in the meat industry. For instance, cattle occupies 84% of the total area under agricultural and livestock use in Brazil (Nepstad et al., 2008) and is a major source of deforestation (Briceño-León, 2007). The extensive production systems (EPS) share features with the two production systems. On the one hand, EPS seek to increase their production for commercial objectives (export). In this regard, these EPS generate similar externalities to intensive farming (transportation, close genetic proximity, prophylaxis, deforestation, etc.). On the other hand, animals in EPS are typically raised outside (pastures) or with outdoor access (*free-range* farms), which increase the chances of contact with wildlife. While animals in EPS are more likely to be monitored and have a greater access to preventive veterinary care than those in BPS, they have similar risks of contact with wildlife, which makes them more vulnerable to infectious diseases. Laddomada et al. (2019) show, for instance, that free-range pigs in Sardinia are an important vector of the African Swine Fever, as they share the same habitat as wild pigs (Costard, et al. 2013; Iglesias, et al., 2017). Similarly, pastoralism systems in Africa have been shown to be a risk factor for zoonotic diseases, including anthrax, brucellosis, Q-fever, rabies, and the Rift Valley Fever (Rass, 2006; Desta, 2016).

5) Biodiversity and other indirect environmental impacts

The increase in animal farming is also a threat to human health as it contributes to the loss of biodiversity. First, the global increase in meat consumption results in increased deforestation either to create new pasturages or to grow soy to feed farmed animals (De Sy et al., 2015). In addition to the negative impacts of deforestation on climate change, environmentalists have sought to understand whether or not the destruction of natural habitats and the associated loss of biodiversity increases the risks of new epidemics. Second, bushmeat production also contributes to the loss of biodiversity as it removes parts of the food chain from the natural habitat and leads to what conservationists call “empty landscapes” (Ripple et al., 2016).

The dilution effect states that biodiversity loss is associated with greater disease risks. Researchers who support the dilution effect explain that encroachment into natural habitats increases the number of small-bodied pathogen-carrying animals (such as rodents). The hyperabundance of these hosts has been shown to result from a significant decrease in the numbers of predators and competitors and an increase in available resources (Levi et al., 2016). The dilution effect has been supported by numerous studies (e.g., Ostfeld, 2013); for instance, Young et al. (2014) show that the decline of wildlife in East Africa has resulted in a significant increase in rodent-borne zoonosis. In contrast, other researchers argue that more highly biodiverse environments may be associated with more diseases (Wood et al., 2014, 2016, 2017). Young et al. (2017) explain that biodiversity is multidimensional and can have multiple definitions, which makes it difficult to draw any general conclusions on the relationships between decreased biodiversity and diseases. Still, the current balance of evidence seems to support the dilution effect: in a meta-analysis of 202 effect sizes, Civitello et al. (2015) find broad evidence supporting that anthropogenic declines in biodiversity are associated with increased risks of human and wildlife diseases.

Meat production has other indirect environmental impacts on infectious diseases, in particular through water use. Agriculture uses more freshwater than any other human activity, with nearly a third required for livestock. Water used for growing animal feed accounts for 98% of the total water footprint of livestock production (Godfray et al., 2018). Although there is considerable variation in water footprint among types of meat and production systems, the production of animal-based products usually requires much more water per calorie or per protein than plant-based products (Poore and Nemecek, 2018). However, the global indirect effect of animal production on infectious diseases through water use is complex. Agricultural development has driven the development of dams, reservoirs and irrigation schemes, which tend to increase infectious diseases such as malaria, and aggravates health burdens by macroparasites such as Schistosoma worms in Sub-Saharan Africa, partly because of an increased freshwater habitat for intermediate snail hosts (Ghebreyesus et al., 1999; Rohr et al., 2019; Sokolow et al., 2017). Yet, agricultural development has also caused a decline in the number and size of wetlands, which leads to a decrease in the emergence of infectious diseases (Rohr et al., 2019).

Animal farming worldwide generates approximately 14.5% of greenhouse gases emissions, and about twice this share if the opportunity cost of land use is accounted for (Poore and Nemecek, 2018; Searchinger et al., 2019). This may generate additional indirect impacts on infectious diseases. Global climate change is shifting the distribution of infectious diseases in humans and wildlife (Lafferty, 2009), and is making the future less predictable because of the nonlinear responses of parasites and hosts to temperature and climatic variability (Raffel et al., 2013). Climate change also affects biodiversity loss which has an impact on infectious diseases as discussed above. Moreover, climate change is expected to have major consequences for morbidity and mortality due to nutrient-deficient diets in the developing world. However, there still exists a high level of high scientific uncertainty and controversy around the climate change/disease relationship, and this issue is considered as an important topic for future research (Lafferty, 2009; Rohr et al., 2011). Finally, we emphasize that agriculture, and especially animal agriculture, is also a major contributor to air pollution, mostly through the emission of ammonia, which is a precursor to fine particles (Tschofen et al., 2019). Although more research is needed on this issue, the health impacts of several infectious diseases, such as COVID-19, may increase when the air quality deteriorates, so that animal farming may indirectly aggravate health impacts through its contribution to air pollution.

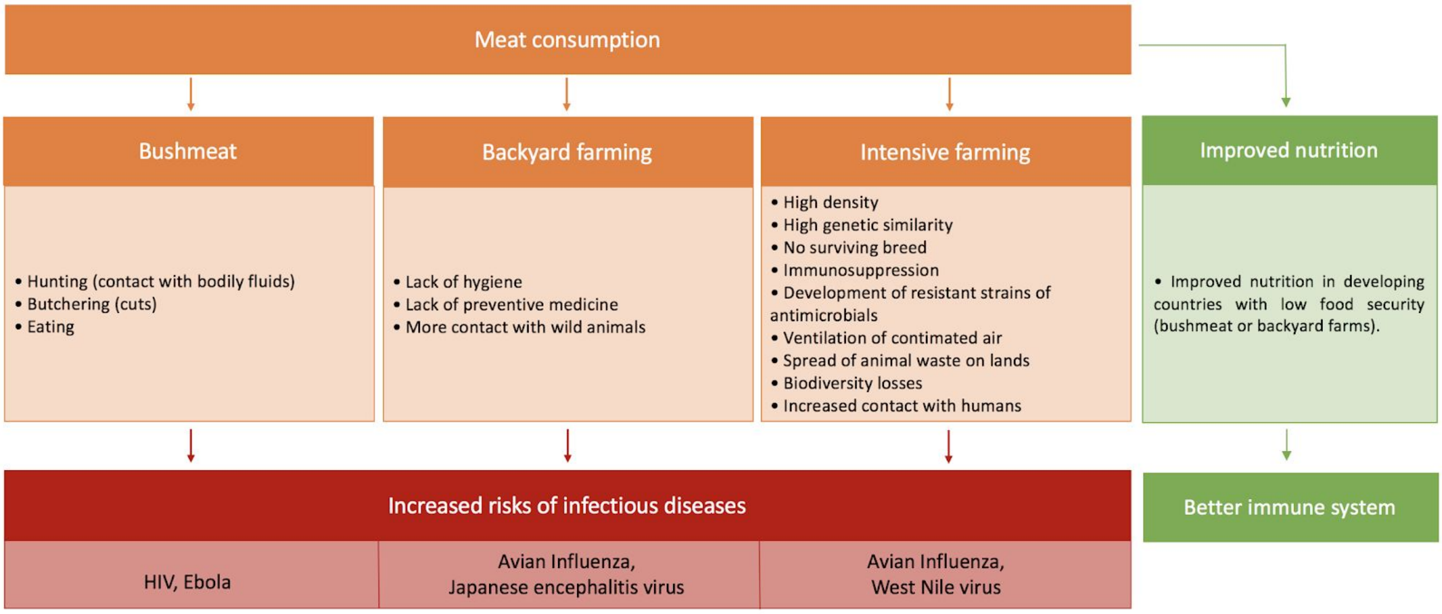


Figure 1: Impact of meat consumption and production on infectious disease risks.
Semi-intensive / extensive farming shares features of the backyard and the intensive farming methods.

III) The costs of infectious diseases

All types of meat production increase zoonotic risks. Efficient food and health policies must take into consideration these externalities in their cost-benefit analysis. The burden of animal-based infectious diseases can be classified in terms of costs directly associated with the disease created by the host-pathogen interaction and those associated with prevention and control measures implemented (see Figure 2). In the case of zoonoses, which are an element of a broad ecological concept of health systems, a holistic understanding of their associated costs is required to better evaluate investments for preventing and controlling such diseases (Zinsstag et al., 2007). While efforts to estimate the burden of diseases have been fruitful (Lopez et al., 2006; Stein et al., 2007), the estimation of the burden of many zoonotic diseases remains incomplete (Torgerson and Macpherson, 2011). For instance, assessing the cost of infectious animal diseases is often limited to farm costs (Bennett, 2003) and more comprehensive methodologies result in estimates that are not fully comparable (Barratt et al., 2019; Saatkamp et al., 2016). Therefore, there is a need to further develop a widely accepted standardized approach to estimate the burden of infectious diseases, which includes the human, animal, and environmental dimensions (Rushton et al., 2018).

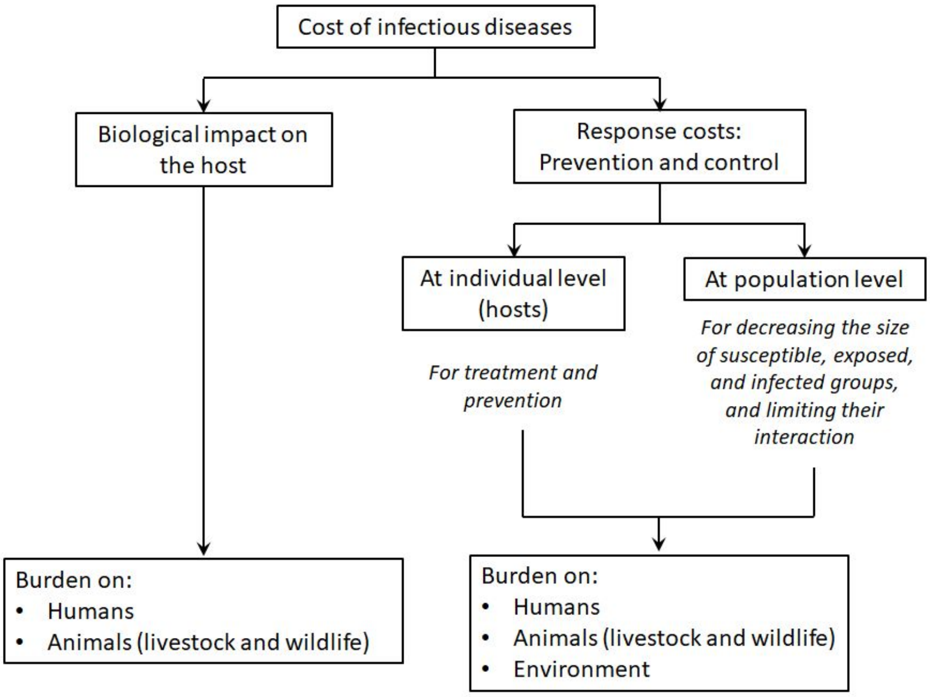


Figure 2: Classification of the cost of infectious diseases

1) <u>Direct costs: the biological impact</u>

The costs associated with a disease triggered by infection with pathogens, also referred to as the biological impact, includes illness, disability, and death in humans, as well as morbidity and mortality in animals (Narrod et al., 2012). Morbidity in livestock is associated with reduced productivity, including fertility problems (Knight-Jones and Rushton, 2013), where the associated monetary value is usually attributed through existing market values. Livestock diseases have a direct impact on the livelihoods of people raising the animals, and more generally on stakeholders of the value chains of livestock and livestock products (Rushton, 2003). The costs associated with the biological impact on animals could be higher—perhaps much higher—if an intrinsic value of animals is recognized instead of limiting the value of animals to their instrumental use to humans, as proposed by some conservationists (Batavia and Nelson, 2017) and economists (Carlier and Treich, 2020). Moral costs associated with humans' altruistic disutility regarding animal welfare loss could also be introduced based on standard valuation methods (Clark et al., 2017), but this has so far been ignored in animal health impact studies.

Two of the most studied diseases so far are Foot-and-mouth diseases (FMD) in cattle, and influenza in humans. The median annual cost of FMD due only to tangible production losses in affected livestock has been estimated at $US7.6 billion worldwide (Knight-Jones and Rushton, 2013). The annual global expected economic cost attributed only to the increased human mortality of pandemic influenza has been estimated to roughly $US490 billion, or 0.7% of the global income (Fan et al., 2016). Further, there is an opportunity cost since the resources of the health system which are devoted to fighting the pandemic could have been used to treat the people with other diseases. Attributing a monetary value to wildlife and wildlife disease losses is more complicated since market valuation information remains scattered and does not capture all of the benefits associated with wildlife, such as contemplating benefits, seed dispersal, and even enhancing the carbon storage capacity of forests (Chardonnet et al., 2002; Berzaghi et al., 2019). Non-market approaches have been adopted to address this challenge but there exists a longstanding debate around its appropriateness (Stevens et al., 1991).

Influenza has been identified as the most likely pathogen to cause a severe pandemic (Madhav et al., 2017), with the H7N9 subtype ranking the highest regarding potential pandemic risk according to the US Centers for Disease Control and Prevention (CDC, 2017). A zoonotic disease prioritization exercise conducted in seven low- and middle-income countries ranked zoonotic influenza as one of the top-three zoonoses of the highest concern (Salyer et al., 2017). Therefore, the pandemic risk associated with the raising of livestock differs by species, with swine and poultry identified as the most common hosts of zoonotic influenza viruses (WHO, 2018).

2) Indirect costs: the response

When responding to infectious events, measures to prevent and control the spread of diseases are usually implemented. At the individual level, such measures aim at reducing the risk of infection (prevention) and mitigating the impact of the disease (treatment). At the population level, the goal is to reduce the size of susceptible, exposed, and infected groups, as well as to limit contact between these groups. These measures can be implemented by governments in order to protect global health, but they can also be the result of self-protective behaviors (Funk et al., 2010). Declaring a notifiable disease can trigger bans from importing countries, which can lead to substantial economic losses for the exporting countries (Blayney, 2006).

Although necessary to reduce the biological impact of infectious diseases, most preventive and control measures are costly, and such costs should—to the greatest possible extent—be carefully analyzed when assessing interventions, especially when they are implemented on a large scale. On the animal side, measures include the application of curative treatments and preventive interventions, such as vaccination and enhanced biosecurity, but also in the costs related to setting up surveillance systems (FAO, 2016), and limiting disease transmission, such as market interventions (Peiris et al., 2016), animal movement controls (Fèvre et al., 2006), and mass culling. Some of these interventions induce substantial economic costs to stakeholders along the livestock value chain and a significant level of animal suffering (te Beest et al., 2011). For instance, with the African Swine Fever, there was a contraction of more than 40% in China's swine inventory within the first year (Haley and Gale, 2020), which represents almost a quarter of the global swine herd. Culling operations involving thousands of animals are logistically challenging and usually come at the expense of animal welfare. While some of these measures are needed to control infectious diseases, some others seem unjustified and can threaten wildlife species (Zhao, 2020).

In humans, curative treatments are prescribed and vaccination campaigns are implemented if available. Enhanced hygiene in human settings, such as hand-washing or mask-wearing, and social distancing measures, including isolation and quarantine, are adopted in the early stages of an outbreak, but they may not be sufficient to contain an epidemic (Wilder-Smith and Freedman, 2020). As the situation evolves, governments may take more aggressive measures to contain the spread, ranging from school closures (Viner et al., 2020) to declaring temporary curfews and imposing lockdowns in entire cities (Lau et al., 2020). Preventive measures of this nature halt economic activity, fuel unemployment (OECD, 2020a), disrupt supply chains of essential goods and services (FAO, 2020c), and ultimately compromise the progress made towards the United Nations Sustainable Development Goals (Solberg and Akufo-Addo, 2020).

During the COVID-19 pandemic, the impact of each subsequent month of strict containment measures has been estimated to be the equivalent to a loss in GDP growth of two percentage points (OECD, 2020b). Moreover, essential health services have been disrupted and catastrophic scenarios seem likely if the curtailment of such services extends, ranging from an increase in new HIV infections among children, now up by more than 70% in some African countries (Jewell et al., 2020), to a decrease in the delivery of childhood vaccines in the US (Santoli et al., 2020). Using a general equilibrium model, McKibbin and Sidorenko (2006) estimate that an extreme pandemic influenza event could cost $US4.4 trillion to the global economy, leading to income losses exceeding 50% of the gross national income in some low- and middle-income countries.

As shown during the COVID-19 pandemic, the environment in which prevention and control measures are implemented is characterized by a high degree of uncertainty. Such uncertainty has an additional toll on the aggregate demand, employment, trade, and the functioning of financial markets, which exacerbates the challenges for recovery after the pandemic is under control (Leduc and Liu, 2020). Although preventive and control measures should be designed according to scientific evidence, the urgency and fear generated by epidemics can coerce people to rush and to implement measures that lead to additional costs. Some examples that have raised concerns among the scientific community are the adoption of treatments that have not been validated (FitzGerald, 2020) or discriminatory behaviors towards stigmatized groups (Rzymski and Nowicki, 2020), the costs of which are hard to quantify.

On the environmental dimension, infectious diseases can have mixed consequences. Helm (2020) differentiates short- and longer-term environmental impacts expected from a pandemic, based on the COVID-19 experience. On the one hand, short-term impacts can be positive, such as the reduction of greenhouse gas emissions due to the contraction in economic activity or the increased connectivity between animal populations; on the other hand, additional waste related to disposable protective gear, as well as reduced environmental monitoring and regulation enforcement during a lockdown, are some of the challenges posed during a pandemic. For instance, hospitals at the epicenter of China's epidemic increased their medical waste by more than 350% compared with pre-outbreak levels (Klemeš et al., 2020; Zambrano-Monserrate et al., 2020). Moreover, immediate climate action may be seen as a less pressing issue by policymakers, which can lead to a relaxation of environmental regulations and diverting resources in order to mitigate the economic costs of the pandemic.

In the longer-term, Helm identifies three policy options that countries may put in place as a response to sharp declines in GDP attributed to the COVID-19 pandemic: monetary easing, fiscal stimuli and infrastructure packages. These measures all aim to stimulate the aggregate demand but can come with negative environmental impacts in the longer term. To counteract this risk, such measures should be complemented with environmental policies, such as those promoting investments in renewables and nuclear electricity, or in other natural capital enhancement projects. The author also identifies potential impacts on globalization and trade, intergenerational imbalances and consumer behavior, which can ultimately have an effect on the environment but which are hard to predict.

3) The unequal burden of infectious diseases

Infectious diseases also have an impact on inequality, as they tend to disproportionately affect the poor. Poverty and inequality create conditions that facilitate the transmission of infectious diseases, which can further contribute to unequal burdens of morbidity and mortality (Quinn and Kumar, 2014; Holtgrave and Crosby, 2003). The COVID-19 mortality risk amongst the poorest populations could be exacerbated considering that such populations are more likely to suffer from chronic conditions and a lack of access to health services (Ahmed et al., 2020). Communities of color have also been disproportionately impacted by the COVID-19 pandemic in the US, due to structural factors that prevent those communities from practicing social distancing, such as their disproportionate participation in "essential jobs" (Van Dorn et al., 2020). A COVID-19 mass testing campaign conducted in San Francisco, revealed that transmission was higher amongst people in the low-income group (Fernandez and Weiler, 2020) and those who cannot confine themselves at home due to the risk of losing their jobs, or because they are providing essential services.

Similar or even more severe challenges can be expected in developing countries characterized by large informal economies and the lack of safety nets. Overcrowded living conditions make the implementation of social distancing extremely difficult (Bong et al., 2020) and highly prevalent comorbidities can lead to higher infection and fatality rates (Dahab et al., 2020). For people employed in the informal sector, not working and staying home means losing their livelihoods and facing food insecurity (ILO, 2020). Moreover, the capacity of intensive care units in low- and middle-income countries is limited and its expansion to avoid saturation levels may not be feasible (Hopman et al., 2020). Overwhelmed health systems are a major risk for developing countries as resources to deal with other diseases are reallocated in order to deal with the epidemic, leading to the disruption of routine health care.

IV) Improving the current regulation of meat production

In the previous sections, we have discussed how animal farming and animal consumption may generate epidemic outbreaks and have described the various consequences of these outbreaks. To do so, we have presented a large set of scientific references in global health, animal health, environmental, agricultural, and economic sciences. In this section, we discuss the existing regulatory framework of animal infectious diseases, and some ways to improve it.

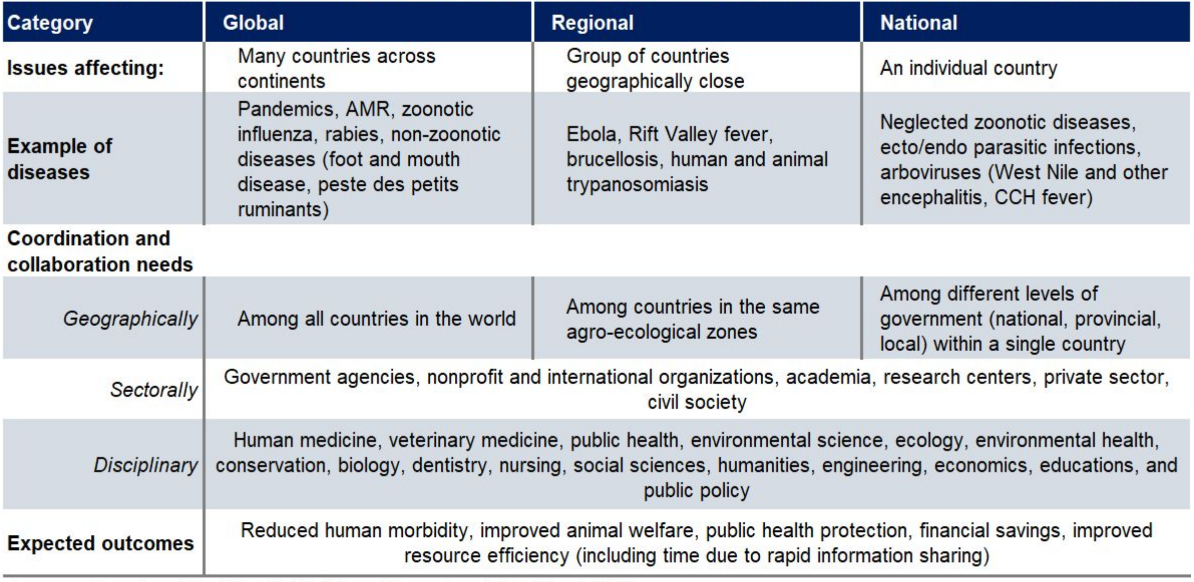
1) Existing regulatory framework

Important regulatory structures have been put in place over the years in order to mitigate the risks associated with animal-based infectious diseases. They include various national and international biosecurity protocols and sanitary standards to monitor, prevent and control the transmission of infectious diseases, the waste products such as excrement or carcasses, the transport of live animals nationally and across borders, and the possibility of contamination during the slaughter and processing phases. The current regulatory framework recognizes the benefits of adopting a One Health approach to address global health threats at the interface of public health, animal health (both domestic and wildlife) and the environment. The One Health approach is a collaborative framework to enhance multidisciplinary and cross-sectoral mechanisms, at global, regional, and national levels, aiming at attaining optimal health for people, domestic animals, wildlife, plants, and the environment (Gibbs, 2014).

Building on this approach, the recent *Tripartite Guide to Addressing Zoonotic Diseases in Countries* involving the Food and Agriculture Organization (FAO), the World Organisation for Animal Health (OIE) and the World Health Organization (WHO) emphasizes the importance of communication among and between stakeholders, strategic planning and emergency preparedness, surveillance of zoonotic diseases, information sharing, and risk assessment (FAO, WHO and OIE, 2019). While the interest of the One Health approach seems to be widely accepted, its operationalization has proven challenging due to the lack of institutional structures that support coordination among sectors. The role of economics, as a discipline that examines trade-offs in scarce resource allocation, has been pointed as crucial in operationalizing the One Health approach (Häsler et al., 2012). This has been reflected in the engagement of the World Bank which developed an operational framework for One Health systems (World Bank Group, 2018) that highlights the need for global, regional and national coordination (Table 1). Countries that provided an appropriate institutional structure to support One

Health may be more successful in translating One Health into action. For example, Indonesia created the Coordinating Ministry of Human Development and Culture (Kemenko PMK), which was designated as the authority responsible for enforcing close coordination among relevant ministries to operationalize One Health. As a result, the government of Indonesia was able to develop an Antimicrobial Resistance National Action Plan that integrates the views and inputs of the Ministries of Health (MOH), Agriculture (MOA), Finance (MOF), and Marine Affairs and Fisheries (MMAF), and which has been translated into actions, such as the implementation of surveillance systems in human and animal settings and multisectoral risk assessments.

Table 1. Issues, coordination and collaboration needs and expected outcomes of One Health at global, regional, and national levels



Category	Global	Regional	National
Issues affecting:	Many countries across continents	Group of countries geographically close	An individual country
Example of diseases	Pandemics, AMR, zoonotic influenza, rabies, non-zoonotic diseases (foot and mouth disease, peste des petits ruminants)	Ebola, Rift Valley fever, brucellosis, human and animal trypanosomiasis	Neglected zoonotic diseases, ecto/endo parasitic infections, arboviruses (West Nile and other encephalitis, CCH fever)
Coordination and collaboration needs			
Geographically	Among all countries in the world	Among countries in the same agro-ecological zones	Among different levels of government (national, provincial, local) within a single country
Sectorally	Government agencies, nonprofit and international organizations, academia, research centers, private sector, civil society		
Disciplinary	Human medicine, veterinary medicine, public health, environmental science, ecology, environmental health, conservation, biology, dentistry, nursing, social sciences, humanities, engineering, economics, educations, and public policy		
Expected outcomes	Reduced human morbidity, improved animal welfare, public health protection, financial savings, improved resource efficiency (including time due to rapid information sharing)		

Sources: Based on World Bank (2018) and Barrett and Osofsky (2013)

This approach requires great deal of control and coordination, and necessitates important investments. It tends to favor the evolution towards intensification through large-scale industrial farms. Some animal health experts and policy makers in both developing and developed countries indeed appear to accept that industrial farming has higher biosecurity standards (Otte et al., 2007; Zhang et al., 2017). However, this trend towards intensification also generates an increase in sanitary risks because of the various factors exhibited in Section 2. The performance of agricultural intensification in terms of risk prevention seems at best questionable if we judge by the increasing number of emerging infectious diseases in recent years (Jones et al., 2008; Coker et al. 2011; Bui et al., 2017). For instance, Dhingra et al. (2018) find that from 1959 onwards there was a total of 39 independent events where a low pathogenic avian influenza converted into a highly pathogenic one. All but two of these events were reported in commercial poultry production systems, and a majority of these events took place in high-income countries (we note, however, that there may be a reporting bias). In addition, the recent expansion and intensification of agriculture disproportionately occurs in tropical and developing countries where 75% of deaths are attributable to infectious diseases, where the risk of disease emergence is usually the greatest, and where the health systems are the most vulnerable (Rohr et al., 2019).

In 2010, less than 18% of the poultry and 35% of the pigs raised globally belonged to backyard or extensive systems (Gilbert et al., 2015). Moreover, as GDP per capita is negatively correlated with the share of livestock raised in extensive systems (see Figure 3), it can be expected that the livestock industry will intensify as developing countries get richer, at least under a business-as-usual scenario.

According to Gilbert et al. (2015), countries with a GDP per capita above $US10,000 (PPP) raise around 90% of their poultry in intensive systems, which could be a result of stronger economic incentives to invest in intensification as the demand for animal products increases due to higher incomes, as well as increasing access to resources to fund the high fixed cost of factory farms in an economy with rising income. Therefore, focusing on intensive systems when designing better regulation and aligning incentives could be a good strategy to reduce the future risks of zoonotic infectious diseases.

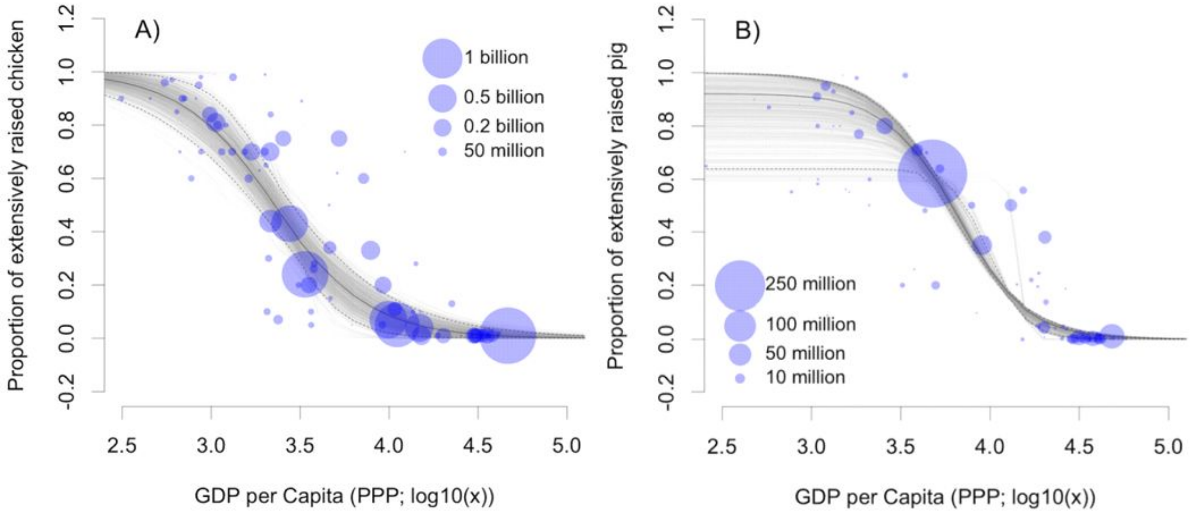


Figure 3: Proportion of extensively raised chickens (A) and pigs (B) from Gilbert et al. (2015). *Each dot represents a country with the size indicative of their stock of animals. The chicken extensive system follows FAO's sector 4 definition (village or backyard production with minimal biosecurity), while pig extensive system is characterized as usually unconfined, with typically <10 pigs, with low biosecurity with little or no health care. The complementary percentage (1-Proportion of extensively raised) represents the proportion of animals raised in intensive systems for chickens, and the proportion of animals raised in intensive and semi-intensive systems for pigs.*

There have been various commentaries and reports suggesting ways to improve the regulatory framework of animal-based infectious diseases (e.g., Karesh et al., 2012; Levi et al., 2014; Gostin, 2016; GPMB, 2019; Di Marco et al., 2020). These works typically emphasize the need to improve preparedness and coordination at a regional and global level and to accelerate research and development on vaccines and treatments, but do not seem to question the evolution of our food systems more broadly, in a context where current dietary choices appear unsustainable. It is also informative to observe that calls for improving regulation have been repeatedly made in the last decades, such as after the influenza A H1N1 outbreak (e.g., Coker et al., 2011). In the rest of this discussion, we emphasize two directions toward a better regulation that, we believe, have so far received insufficient attention both in academia and policy making fields. One direction concerns the supply-side and is presented now, while the other concerns the demand-side and is presented in the next Section.

2) Better aligning stakeholders’ incentives

The first direction to reduce the zoonotic externalities of meat production, obvious for economists, consists of better aligning the stakeholders’ incentives with the common good. We first observe that the consequences of epidemics are mostly supported by the public, first through people’s morbidity and mortality and also because most financial consequences are borne by the health and public finance systems (see Section 3). Moreover, national or international agencies working on animal infectious disease prevention are usually publicly funded. In 2015, the funding for the investigation of emerging and zoonotic diseases in a single public US institution, the Centers for Disease Control, was nearly half a billion dollars (Schuck Paim and Alonso, 2020). In their survey analysis, Rushton and Gilbert (2016) find that more than three quarters of the cost of worldwide veterinary services for animal health are funded by the public sector. Various other induced costs of animal outbreaks such as preventive animal culling may also be a burden for the taxpayer as farmers are often compensated ex post for the economic cost of culling. Farmers also often receive subsidies for vaccines, veterinary services, and the modernization of livestock facilities, which covers biosecurity (OECD, 2017). The search and population control of wild animals living around farms is also typically carried out by public authorities; for instance, the control of African Swine Fever in South Korea was performed by the Ministry of Environment (100 persons), the Forest Service (200) and the military from five divisions (Jo and Gortazar, 2020).

The consequence of the financial and logistic involvement of the public sector is that the infectious disease risks to animal and public health arising from livestock production may not be properly reflected in the costs of production, and in turn by the prices of animal source foods. This does not sound economically logical, in a context where the prices of food products do not well reflect their environmental externalities either (Bonnet et al., 2020; Nature Food, 2020a). This regulatory failure largely favors the most polluting products, namely animal-based products over plant-based products (Poore and Nemecek, 2018). If there are different ways of producing food associated with different levels of risk, and if one way is more risky than the others, it should be that the burden of risk is reflected in food prices in order to provide better incentives to consumers. Hence, costs should be better internalized by polluters, for example, farmers, meat processors, and eventually the consumers of animal products. The key question is *how* to do this.

Although farmers have clear incentives to prevent livestock disease, diminishing the prevalence of infectious animal disease generates positive externalities, so that government intervention is justified. However, appropriately designing public intervention requires a clear understanding of private incentives and strategic interactions (Hennessy, 2007). For instance, farmers have private information about preventive biosecurity measures they adopt and about whether or not their herd is infected (Gramiget al., 2009). Some farmers may actually gain from an animal disease outbreak affecting others (Otte et al., 2007). The localization of farms matters for self-protection incentives (Hennessy, 2007). Since the spread of infectious diseases depends on the openness of the production system, an appropriate trade policy is also warranted. Current economic policy approaches mostly focus on pandemic insurance, namely mobilizing resources for post-outbreak response and recovery in affected countries (Di Marco et al., 2020). However, if farmers know they are going to be compensated by the government, there is an additional moral hazard problem. Interestingly, approaches to ex post compensation related to epidemic diseases differ widely across countries: for instance, Australia establishes a cost-sharing rule between industry and government, Korea tailors government partial compensation to particular farmer profiles, while Chilean regulations do not foresee indemnities to producers in the case of animal disease outbreaks (OECD, 2017).

When disease outbreaks occur, the initial source of contamination as well as some possible producers' negligence may be difficult to identify, complicating the implementation of sanctions and liability rules. Farmers should be incentivized to report a disease outbreak, especially for *early* reporting. To date, most regulatory measures of animal infectious diseases consist of "command-and-control" measures. It is not clear that these measures optimally account for the various strategic considerations involved, even in a second-best world (Gramig et al., 2009); at least, we are not aware of solid theoretical and evidence-based economic analysis to support existing regulations. The spread of animal infectious diseases is fundamentally a dynamic and uncertain phenomenon, which complicates understanding and policy implementation. The risk preferences and perceptions of farmers may also play an important role in the adoption of private control measures during an epidemic. We thus conclude this Section by emphasizing the possible role for economists in an integrated interdisciplinary approach to better aid policy making in order to prevent the risks associated with animal infectious diseases (OECD, 2017; OECD-Joint Risk Assessment, 2020), as well as the research potential for environmental economists, who have a considerable experience in policy design in situations involving externalities, asymmetric information, dynamics, and uncertainty.

V) A new paradigm: reducing meat consumption

In this final part, we emphasize another regulatory direction. As illustrated in the previous Section, essentially all the literature on animal infectious disease prevention, including various reports produced by international institutions such as FAO, WHO, OIE or the World Bank, concentrates on the supply side. It typically overlooks the issues related to the demand for meat, or essentially takes this demand as exogenously given. But meat production increases because there is a demand for it. In 50 years, between 1960 and 2010, the global stocks of chickens and pigs increased by factors of 5 and 2.5, respectively (Gilbert et al. 2014). In Asia, during this period, meat consumption has been multiplied by 15 while population has been multiplied by 2.6. While designing the regulation of the supply side is highly complex as argued above, in contrast, reducing meat consumption appears to be a silver bullet. Since not one single pandemic in human history can be traced back to plants (Schuck Paim and Alonso, 2020), substituting animal-based food with plant-based food should largely reduce overall zoonotic risks. In other words, a shift to more sustainable plant-based proteins should offer resilience where various forms of animal protein production have failed. This advantage should then be added to the long list of benefits of reducing meat consumption, including the decrease in greenhouse gases emissions, air pollution, land use, water use, water pollution, and likely the incidence of major noncommunicable diseases in developed countries (i.e., cancers, diabetes, cardiovascular diseases) (Godfray et al., 2018; Poore and Nemecek, 2018; Tschofen et al., 2019; Willett et al., 2019).

Note that, while we emphasize the advantage of reducing meat consumption to reduce infectious disease risks, we did not discuss to any great extent the choice between different meat products, and thus between animal production systems, for instance between intensive versus extensive agriculture. One reason is that we discussed (to some degree) the relative weaknesses of each animal food systems in Section 2. In addition, this choice is still a matter of scientific debate, as illustrated, for instance, by the *land sharing* versus *land sparing* controversy regarding the impact of agriculture on biodiversity and losses of natural habitats (Kremen, 2015). However, the main reason, as we will further argue below, is that reducing meat consumption and in turn downsizing meat production will probably deliver risk reduction benefits on a scale not achievable by marginally changing our existing animal food systems. That is, we believe that targeting the demand side of meat may be more effective than targeting the supply side for structural reasons.

Supply side strategies regarding the agricultural sector have indeed been notoriously complicated to implement in the past, as is well documented in the environmental domain for instance. It is common knowledge that the greening of common agricultural policy globally is a failure (Pe'er et al., 2014). Also, the agricultural sector has been largely exempted from climate change policies (e.g., carbon tax or emissions trading systems), and from air pollution regulation such as the Clean Air Act. One of the main reasons for this apparent regulatory failure is that the agricultural sector has strong political ties (Simon, 2013), and is thus difficult to regulate. Moreover, this regulation is complicated by the high degree of competitiveness of world agricultural markets, and the fact that most farmers are poor or very poor, even in developed countries. Another reason is that regulating the agricultural sector is often perceived negatively by the public since it is associated with food insecurity and viewed as a barrier to the provision of basic needs.

This last concern is a legitimate issue, especially in developing countries. It should be recalled that about 10% of the world population live in a chronic state of malnutrition. The nutritional role that meat can play in countries facing malnutrition and food insecurity should not be neglected (see Figure 1). For instance, Nielsen et al. (2017) estimates that more than one third of the population of Latin America, Asia, and Africa harvests bushmeat. While this meat contributes little to rural household income (about 2%) and mainly through own consumption (87%), reliance on bushmeat appears more important in smaller and more remote communities (but not in China where more educated and richer people consume more bushmeat; Zhang and Yin (2014)). Hence, regulating bushmeat consumption and trade is challenging, as the associated revenue can be essential for the subsistence of some families living in extreme poverty (De Merode et al., 2004; Kümpel et al., 2010). Also, after the COVID-19 pandemia which probably originated in wet markets in China, an increasing number of voices are calling for a ban of these markets (Zhang et al., 2014). But, again, wet markets support livelihoods, including those of small producers and farmers, and they are an important source of food for many communities (Nature Food, 2020b). Moreover, some researchers note that bans could actually increase the infectious disease risks by shifting these activities into illegal and unregulated markets (Webster, 2004; Nguyen et al., 2017) and accelerate the transition to intensive farming systems, which in turn present a higher risk for the evolution of highly pathogenic strains and disease amplification. Overall, we conclude that the case for regulating meat consumption in poorer countries is much weaker.

An additional complexity for regulation is that the risks associated with infectious diseases have a catastrophic aspect. The COVID-19 pandemic economic relief plans announced by countries have allocated an unprecedented amount of resources, often representing around 5 and up to 20% of annual GDP. This catastrophic aspect makes the design of insurance schemes extremely difficult, if not impossible. There is then a simple economic rationale here: if the risk is difficult to manage and anticipate, and can hardly be shared once it occurs, the role of early self-protection becomes further emphasized; specifically, reducing the probability of a pandemic at the source. This can typically be achieved by reducing the consumption and production of animals. Therefore, we conclude that, in a growing and wealthier world, while the demand for meat is expected to drastically increase in the coming decades if no alternatives are adopted, and while animal agriculture tends to intensify everywhere in this world, it appears more and more urgent to find ways to curb the demand for meat (Godfray et al., 2018)

But how? Given that infectious diseases can be viewed as an externality generated by food choices, we could naturally consider a Pigouvian tax on the consumption of animal products, say a “zoonotic tax”. While no country in the world has yet implemented a carbon tax on animal products, this raises the question of the alignment of a carbon tax and a zoonotic tax. A carbon tax mostly targets ruminants' meat and dairy products (Godfray et al., 2018; Bonnet et al., 2020). This may not be the case for a zoonotic tax, however, which would principally target pork and poultry meat in particular, as discussed in Section 3. Nevertheless, a global difficulty is that regulators may not have the societal license to tax meat products, whether for climate, infectious diseases or anything else. Furthermore, people seem strongly attached to eat meat because of a mix of biological, sociological and cultural factors, and it is extremely difficult to change ingrained food habits (Graça et al., 2015). Regulators may then have to resort to a subtle combination of fiscal, informational and behavioral instruments (Godfray et al., 2018; Bonnet et al., 2020). For instance, using nudges such as vegetarian default options (Hansen et al., 2019) or promoting step-by-step collective initiatives such as meatless days (Bonnet et al. 2020), may prove effective. Moreover, it may be important to review the role of plant-based diets in official nutritional recommendations/guidelines in order to account for the associated reduction in transmissible health risks induced by infectious diseases.

As a longer term strategy, regulators may rely on innovations and encourage the development of protein alternatives such as processed plant-based protein like tofu, seitan, mycoprotein, or fungus, as well as high tech options, such as plant-based burgers. Eating insects, for instance in the form of flour made from crickets or otherwise, may also be promising (van Huis, 2019). Insects, which are evolutionary so distant from humans, should not pose great zoonotic risks (Dicke, et al. 2020), although this is a controversial and under-researched issue (Gałęcki and Sokół, 2019). Moreover, farming and eating insects may avoid raising strong animal welfare issues, and the emission of pollution from insects is relatively low (Kim et al., 2020). Further, insects can be reared on feed that is unsuitable for livestock and which would otherwise have been wasted or have low economic value (World Economic Forum, 2019). Finally, we emphasize the promise of cultured meat, namely meat produced by cultivating animal cells in the laboratory (Stephens et al., 2018; Treich, 2020). In theory, this innovation permits the taste and texture of meat to be reproduced without having to manage the whole process: the rearing, transport and slaughter of animals. Since this technique readily eliminates contact with live animals (except in the early phase to obtain the animal cells), it should drastically reduce the risks of zoonotic disease.

To conclude, and in attempt to summarize succinctly our discussion of regulatory issues in Sections 4 and 5, we provide a Table that includes some policy recommendations.

Table 2. Summary of policy recommendations to regulate meat production (policies 1 and 2) and meat consumption (policies 3 to 5).

Policy recommendations for developed countries	
1.	Adjusting the compensation for the meat industry to reduce the moral hazard, and in particular to incentivize early reporting of epidemic outbreak.
2.	If any, conditioning the subsidies to farms on the production and transportation system (decreasing with the number of farmed and transported animals, decreasing with the genetic proximity, increasing with the use of vaccines, decreasing with the preventive use of antimicrobials).
3.	Implementing a zoonotic tax on animal-based products.
4.	Implementing large-scale informational and nudging policies to reduce meat consumption and promote plant-based diets, and reviewing the role of plant-based diets in official nutritional recommendations/guidelines.
5.	Subsidizing the development of animal-based food alternatives with lower zoonotic risks (insects, cultured meat).

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