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Epidemics in markets with trade friction and imperfect transactions

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AUTHOR-HIGHLIGHTS

- Trade can support the transmission of infectious diseases, but it is not clear how.
- Market dynamics are constrained by trade friction because exchanges have constraints and are costly.
- We develop a model of market dynamics with trade friction and spread of disease.
- Friction can be a stronger determinant of epidemics than other forms of behaviour.
- Lower trade friction requires greater immediacy in implementing epidemic control.

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ABSTRACT

Market trade-routes can support infectious-disease transmission, impacting biological populations and even disrupting trade that conduces the disease. Epidemiological models increasingly account for reductions in infectious contact, such as risk-aversion behaviour in response to pathogen outbreaks. However, responses in market dynamics clearly differ from simple risk aversion, as are driven by other motivation and conditioned by “friction” constraints (a term we borrow from labour economics). Consequently, the propagation of epidemics in markets of, for example livestock, is frictional due to time and cost limitations in the production and exchange of potentially infectious goods. Here we develop a coupled economic-epidemiological model where transient and long-term market dynamics are determined by trade friction and agent adaptation, and can influence disease transmission. The market model is parameterised from datasets on French cattle and pig exchange networks. We show that, when trade is the dominant route of transmission, market friction can be a significantly stronger determinant of epidemics than risk-aversion behaviour. In particular, there is a critical level of friction above which epidemics do not occur, which suggests some epidemics may not be sustained in highly frictional markets. In addition, friction may allow for greater delay in removal of infected agents that still mitigates the epidemic and its impacts. We suggest that policy for minimising contagion in markets could be adjusted to the level of market friction, by adjusting the urgency of intervention or by increasing friction through incentivisation of larger-volume less-frequent transactions that would have limited effect on overall trade flow. Our results are robust to model specificities and can hold in the presence of non-trade disease-transmission routes.

1. Introduction

While it is widely accepted that trade can drive disease epidemics and other biological invasions, the interaction of these processes with the inherent dynamics of markets remains unclear. Economic markets can propagate diseases among market agents (e.g. farms) through the exchange of contaminated products (e.g. animals). Conversely, market dynamics are influenced by complex adaptive behaviour of trade agents in response to regulation and individual awareness of epidemics. Markets that contribute to infectious disease epidemics include livestock trade of cattle (Rautureau et al., 2011), swine (Lentz et al., 2011), and sheep (Kiss et al., 2006); prostitution (Rocha et al., 2011); and airline

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transportation (Colizza et al., 2006). Other types of epidemics occur through exchange of information on the Internet (Lloyd and May, 2001) and exchange of debt in financial markets (May and Arinaminpathy, 2010; Haldane and May, 2011).

The likely possibility that there may be an interaction or feedback loop between epidemic dynamics and host behaviour has generally not been considered in studies for identifying effective strategies for the control of infectious diseases. Recent modelling studies, however, have explored the epidemiological impact of one particular response that can cause such an interaction, namely, adaptive risk-aversion (RA) behaviour (Funk et al., 2009, 2010; Durham and Casman, 2012; Nicolaides et al., 2013). RA behaviour is a form of disease prevention where asymptomatic hosts reduce exposure to infection by reducing their contact rate (e.g. by staying home) and/or their probability of infection per contact (e.g. by wearing protective masks); it implies that hosts have some information about a given disease outbreak and act on their own initiative rather than relying on community-wide measures by regulatory bodies. If this behaviour is determined by the ongoing perception of a variable risk, then it is said to be 'adaptive' RA. In the literature, RA has been expressed as a simple function of disease prevalence or outbreak awareness (Funk et al., 2010), or evaluated via complex optimisation of a host's economic weighing between the benefits of interacting with other hosts and the cost of infection that may be acquired through such contacts (Fenichel et al., 2011; Morin et al., 2013). Naturally, epidemiological models that neglect RA behaviour tend to overestimate the probability of occurrence and severity (e.g. infectious peak and cumulative cases) of epidemics (Funk et al., 2009, 2010; Fenichel et al., 2011; Morin et al., 2013). To the best of our knowledge, epidemiological modelling studies have focused on adaptive human behaviour that is altered solely in response to awareness of outbreaks.

In this paper, we investigate the epidemiological effects and implications for disease control of more general human adaptive behaviour, which may be difficult to anticipate. We focus on markets of goods, where the dynamics of potentially infectious contacts are driven, primarily, by economic decisions very different from those underlying disease RA. Specifically, we aim at modelling the influence of market dynamics on the dynamics of infectious-disease epidemics, and in turn, the influence of epidemics on market dynamics. Indeed, when an epidemic shock occurs in a market, the subsequent actions and behaviour may either help us to restore or further disturb the balance between supply and demand. Sanatory regulation and RA aimed at reducing infectious contacts can diminish supply and demand. Conversely, the responses exhibited by market agents can have either positive or negative impacts on disease dynamics. For example, agents that try to establish alternative but potentially infectious trade relationships could outweigh the effect of regulation and RA efforts, i.e. the effort of individual agents to adjust their own supply and demand to changing price could worsen disease outbreaks. Furthermore, the establishment of trade relationships, which underpin the epidemiological contacts, is conditioned by physical impediments such as the minimum time and effort involved. These resources are limited by (i) producing profitable goods (e.g. reproduction and growth of livestock), (ii) searching business partners and cutting deals (e.g. a buyer needs to find a seller with whom to trade a given number of goods at a given market price), and (iii) delivering goods (e.g. organising transport from a buying to a selling holding). In labour economics, such interaction constraints shaping relationships between work sellers and work buyers are known as 'friction' (see the model of Diamond, Mortensen and Pissarides (Pissarides, 1985; Mortensen and Pissarides, 1994; Pissarides, 2011)). We transpose this concept to exchange-markets that can conduce infectious diseases. Therefore, by limiting the development of potentially infectious trade contacts, friction may have a suppressive effect on epidemics. Phenomena such as friction and adjustment in supply and demand illustrate that human behaviour in response to disease epidemics that are supported by trade does not simplify to regulation and RA.

To the best of our knowledge, existing mathematical models of market dynamics do not seem to represent explicitly the variety of transient non-equilibrium dynamics that occur when a market is disturbed and until it eventually reaches a steady-state equilibrium (see ESM Section A); therefore, they may not fully incorporate processes and parameters that establish a time scale for market steady-state equilibration, which is expected to vary widely among markets for rapidly changing external conditions such as those induced by epidemic outbreaks. In order to represent the joint-dynamics of markets and epidemics at appropriate and mutually consistent time scales (see Section 2.1), we have developed a novel economic-market model, the *frictional-trade market (FTM) model* (see Section 2.2), where transient and long-term dynamics are determined by the level of trade friction and agents' decisions to supply or demand goods. Subsequently, we integrate market and epidemiological processes in a *market-epidemiological (ME)* modelling framework where trade influences disease transmission and disease control actions affect trade (see Section 2.3).

We first study the behaviour of the FTM model in the absence of epidemics (see Section 3.1). Then, we investigate how market dynamics affect epidemic development, and, conversely, how epidemics disrupt short- and long-term market dynamics (see Section 3.2). We consider two forms of response to disease outbreaks taken from the literature: the removal (inactivation) of market agents found to be infected by regulators and their later re-introduction or replacement, and an adaptive RA behaviour of market agents. Therefore, we highlight differences in concept and impact on epidemic development between market dynamics and RA; market dynamics are influenced by centrally regulated actions and by collective behaviour that drives changes to supply and demand in response to changing conditions, while RA behaviour is determined solely by individual decision-making. Finally, we extend our study beyond an isolated (e.g. national) market, by contrasting scenarios where infectious diseases are propagated through trade pathways with differing degree of openness to international trade and non-trade disease-transmission pathways. We expect our central results to apply to a range of different types of markets, and illustrate applications to cattle and swine livestock markets in France.

2. Market-epidemiological modelling framework

2.1. Overview

We develop a novel theoretical framework for the propagation of infectious diseases in economic markets where the exchanged goods can transmit an infectious organism between market agents (Fig. 1A). In order to represent this process, we link a model of an economic market system and a model of an epidemiological system. Each model dynamics can exist per se, i.e. epidemics can occur in host populations unaffected by markets, and markets often operate without disease outbreaks through trade routes. However, by building a system that links the dynamics of these subsystems we can study their interdependencies. As the epidemiological model we use is a simple adaptation of a standard compartmental epidemiological model, it is introduced later with brief explanation. The dynamic economic-market model, however, is novel, and is derived in detail. A key property of this model is its coefficient of friction, which characterises a market's inherent