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Economics of invasive pests and diseases: a guide for policy makers and managers

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Keywords: invasive species; pests and diseases; agriculture; forests; zoonotic; transferable externality.

JEL codes: Q01, Q18, Q23, Q54, Q57

ECONOMICS OF INVASIVE PESTS AND DISEASES: A GUIDE FOR POLICY MAKERS AND MANAGERS.

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Invasive pests and diseases are a growing threat to agricultural crops, livestock and forests worldwide. In this report, we look at the contribution that economics can make to developing policies to counter the risks of such pests and diseases. First, though, we review some of the evidence on the nature of this problem.

AGRICULTURE

Pre-harvest pest and disease damage in eight of the most important food and cash crops, is valued at US$300 billion, which accounts for 42% of production (Anderson et al., 2004). One example of an invasive disease of a staple food crop, is Karnal bunt of wheat (*Tilletia indica*) which renders infected crop (such as wheat, durum, rye and triticale) unfit for human consumption. The disease first emerged in 1931 in Karnal, India and was initially restricted to South Asia and Iraq. However in 1972, it was discovered in Mexico, and then in the USA in 1996. Many regions with Karnal bunt are banned from exporting wheat, leading to great economic losses (Anderson et al., 2004). Another example, is potato late blight (*Phytophthora infestans*), which originated from Mexico and was introduced into the north-eastern USA, and then into Europe in the 19th century. It was further introduced to Asia, Africa and South America and then re-introduced into the USA and Canada in 1990s. Blight causes large devastating epidemics globally, notably the Irish potato famine in the 1840s which was responsible for the migration of five million people (Anderson et al., 2004).

Other examples of invasive pest and diseases include: citrus canker (*Xanthomonas axonopodis* pv. *citri*) which can be found in Asia, South America, Oceania (other types of citrus canker can be found elsewhere); beet necrotic yellow vein furovirus (*Rhizomania*) in Asia, Europe and North America; Mediterranean fruit fly (*Ceratitis capitata*) in Asia, Africa, North and South America, Europe and Australia; mosaic of abaca (sugarcane mosaic virus) in most countries which produce sugarcane; African cassava mosaic (cassava mosaic disease) in Africa and Indian Ocean Islands; Citrus greening (*citrus huanglongbing (greening) disease*) in Africa, Asia, North and South America and Oceania; and Rice blast (*Magnaporthe grisea*) in most rice producing countries.

LIVESTOCK

The livestock industry is crucial to developed and developing countries around the world: cow's milk, at US$180 billion, is the second most valued food worldwide, moreover meat of cattle, pig and chickens are worth a combined total of US$462 billion (Slingenbergh, 2013). As with crop production, invasive diseases can have a devastating impact, for example over the last few centuries there have been outbreaks of foot and mouth disease (FMD) in Asia, Africa, North and South America, Europe and Australia. The most recent pandemic occurred in 2001 and resulted in the closing of trade borders to 25% and 40% of world beef trade and global pork exports respectively (Morgan and Prakash, 2006). The cost of the 2001 outbreak is estimated to be US$11.5 billion to the UK economy alone (IFAH, 2012). Subsequently, the disease has been controlled in many areas (Europe, and most of Americas), but Africa and Asia still suffer outbreaks, making FMD one of the most economically significant livestock diseases (IFAH, 2012).

Other examples of invasive livestock pests and diseases include: rabies which causes annual livestock losses estimated at US$1.7 million and US$10.5 million in Africa and Asia respectively (IFAH, 2012); Mad cow disease (*Bovine spongiform encephalopathy*) which was first recognised in the UK in 1986 in cattle, and then spread to many other countries in Europe and then to Japan and North America;

bovine ephemeral fever (*Rhadovirus*) which is mainly restricted to Asia and Africa but outbreaks in Papua New Guinea (1956) and parts of Australia have occurred; and influenza virus A, in particular the highly pathogenic avian influenza, which had 21 outbreaks (mainly in the Americas and Europe) between 1959 and 2003. Many livestock diseases can be transmitted from wildlife. Wild waterfowl, for example, is a reservoir of Avian influenza, which infects poultry. In the US alone an estimated outbreak can cause US$5-212 million in loses (Miller et al., 2013). Another example is Bovine viral diarrhoea virus which can be found in many deer species and also transmit to cattle and bison (Miller et al. 2013). The virus, whilst not lethal can cause large economic losses through reduced productivity. An example of a zoonotic pathogen (a pathogen which transmits from wildlife to humans) is the Ebola virus. It first appeared in Sudan and the Democratic Republic of Congo in 1976. The transmission of Ebola is complex, and currently it is thought that fruit bats are a natural host, and it can then be transmitted to other wildlife species (such as chimpanzees, gorillas, monkeys and forest antelope) and humans. A current outbreak, starting in early 2014, and has since killed approximately 40% of 28,600 the infected people in West Africa. Another zoonotic virus that may potentially have a large impact on human health and wellbeing is Zika virus, which primarily infects non-human primates, but through a mosquito vector spills over to people. Zika may be passed from mother to unborn child causing sever birth defects, which has led some public health agency to recommend that women in infected regions not become pregnant[1].

FORESTS

Invasive pests and diseases also effect forests: since 1860, 62 insect species and 16 pathogen introduced into the USA are considered as having a high impact on forest ecosystems (Aukema et al., 2010). One of the most well-known pathogens in the northern hemisphere is Dutch elm disease (Ophiostoma ulmi and then Ophiostoma novo-ulmi). Dutch elm disease appeared in Eastern Europe and North America in the early 1940s, and then it spread to Asia and the rest of Europe in subsequent decades. It has been re-introduced to many places in Europe and North America, and more recently introduced to New Zealand in 1989. Introductions occur mainly through the trade of timber and other wood products. Today, Dutch elm disease has killed millions of elms (Brasier, 2000), causing large losses to the environment, biodiversity and landscape. More recently, the introduction of Ash Dieback (*Hymenoscyphus pseudoalbidus*) to Europe has received significant media attention due to the extensive damage to European and common ash (*Fraxinums excelsior*). Arriving in Poland (from, probably, Asia) in 1992, ash dieback has since spread to 22 European countries by 2010, resulting in large socio-economic losses. Also affecting ash in North America, the emerald ash borer (*Agrilus planipennis*) has been estimated to kill over 30 million forest and ornamental trees in a decade (Figure 1). The East Asian was

FIGURE 1: EMERALD ASH BORER (AGRILUS PLANIPENNIS) IN A TREE.

[1] http://www.thelancet.com/journals/lancet/article/PIIS0140-6736(16)00006-4/abstract

discovered in Michigan in 202 and since has spread to 15 states in North America. It has also been found in Russia, from where it could spread into Europe.

Pest and diseases also affect commercial forestry. For example, root and butt rot (*Heterobasidon annosum*) is one of the most destructive diseases of conifers in the northern temperate regions of the world. It has a significant impact on timber production resulting in approximately 800 million euros lost annually in Europe alone (Asiegbu et al., 2005). Moreover, the gypsy moth (*Lymantria dispar*), which is prevalent across North America, Europe, Asia and Africa and causes significant damage to numerous host species. In 1993, the pest cost the U.S. Forest Service $10.6 million to control (Campbell and Schlarbaum, 1994) in addition to losses from timber and non-timber services. Other invasive pests and pathogens affecting forests include: sudden oak death *(Phytophthora ramorum)* in North America and Europe (Figure 2); Asian longhorn beetle (*Anoplophora glabripennis*) which is indigenous to China and is now present in other parts of Asia, and sporadically introduced to North America and Europe; Chestnut Blight (*Cryphonectria parasitica*) in North America and Europe, and restricted distribution in Australia; and Phytophthora dieback (*Phytophthora cinnamomi* Rands) which is established in many parts in the world, and is considered to be one of the 100 worst invasive species.

FIGURE 2: PHYTOPHTHORA RAMORUM ON LARCH IN THE SOUTH OF SCOTLAND.

THE ECONOMIC PROBLEM

These pests and diseases have economic impacts on both commercial and wild species; their economic costs thus include those priced by the market (such as lost profits to farmers and foresters) and non-market costs (such as the effects on recreational use of forests and landscape).

Why are such pests and diseases expanding worldwide? Research points to the effects of trade, both between and within countries, climate change, the expansion of exotic (non-native) species outside of their native range, and specialisation which makes crops/forests more vulnerable. Recreational activities can also spread such pests and diseases, for example the movement of infected material, such as spores, on shoes, bikes and another equipment between forests. Responding to pests and diseases in terms of actions which reduce the speed of their spread or their impact are costly for land managers and for regulators; but these pests and diseases can also impose costs on consumers, for example by leading to price rises for affected crops.

Economic analysis of policy and management responses to pests and diseases such as emerald ash borer and dothistroma raise need to take a number of important factors into account, including:

- The effects of international trade on the transfer of pests and diseases across borders: this constitutes a cost to trade which much analysis has not considered;

- That actions by one land-owner can affect the probability that their neighbour will be impacted by a disease; if I take precautionary actions to reduce the chance of a pest invading my forest, or take actions to eradicate a pest on my land, this can change the likelihood that my neighbour's forest will also be affected. There is thus a strategic interdependence between land managers.
- Strategic interactions also occur between counties or countries: what Western Australia chooses to do about a disease in wheat will affect the expected economic costs of the disease in South Australia. How regulators in California respond to a new pest will affect the potential payoffs from actions which neighbouring states might undertake.
- Some diseases can jump between wild and domesticated species, so any optimal control strategy has to take into account both how diseases are transferred, and the dynamics of the costs and benefits of control in both wild and domesticated animal populations.
- For forest pests and diseases, decisions taken today can impact on costs and benefits far into the future (this is less true of agricultural crops and livestock).
- Control options for some pests and diseases are characterised by uncertainty over the spread of the diseases/pest as well as the effectiveness of mitigation options; this uncertainty may fall over time so that we can learn by waiting to act, but is unlikely to be completely resolved. Moreover, waiting to act imposes its own costs.
- Land managers face trade-offs between different attributes of forest or crop types, such as productive yield and disease resistance, whilst ecosystem service benefits might well change if species are chosen which increase disease resistance.
- People respond to disease risk and disease policy by altering their behaviour, in effect to achieve private well-being. Policy responses to infectious agents need to account for private responses and avoid crowding-out private activities that reduce risk.
- How far and how fast a disease or pest spreads across a landscape depends on a complex interaction of economic factors (the behaviour of land managers, for example), environmental factors such as wind and temperatures, ecological factors such as competition for food and space, and the epidemiological drivers of pest and disease dynamics. This fact has given rise to a recent expansion in inter-disciplinary modelling of crop, animal and forest diseases, a literature to which economists have contributed greatly (eg Epanchin-Neil and Wilen, 2014).

This briefing note summarises insights from a symposium organised at the 2015 Bioecon conference in Cambridge, England, where a number of papers on the frontier of this research field were presented[2].

FOREST DISEASES AND OPTIMAL FOREST MANAGEMENT

Two papers in the symposium looked at the implications of pests and diseases for the best way in which forests should be managed. Morag Macpherson and co-authors looks at the effects of different characteristics of diseases on how long trees should be allowed to grow for before being felled in a commercial plantation – the optimal rotation period. The optimal rotation period for a forest is that which maximises the net present value of benefits obtained from the forest over time. Macpherson et al. adapt the classic Faustmann model to consider diseases in a single-species forest, when the problem varies according to:

- how fast the pest or disease spreads; and

[2] These papers are being published in a special issue of Environmental and Resource Economics in late 2016.

- how great an effect the disease or pest has on timber values.

The spread of the disease is represented by a Susceptible-Infected "SI" system – whereby each tree or each patch at any point in time can be classified as either susceptible or infected. The optimal rotation period turns out to depend on a complex interaction between economic, epidemiological and ecological parameters. The main result obtained is that presence of the disease acts to reduce the optimal rotation period, with the owner/manager balancing the net benefits from leaving the forest to grow longer against the increasing spread of the disease over time. As the disease spreads faster, or has a bigger effect on timber values, then the optimal rotation period falls further (see Figure 3 below). This suggests that forest owners will not be willing to let forests stand for as long, when pests and diseases threaten. Since the authors only consider the timber benefits from the forest, an obvious extension is to consider non-timber forest benefits such as recreation and carbon storage/sequestration. Moreover, with two species, forest managers will trade off the relative risks from disease between the two species compared to the other benefits and costs of species choice in deciding how to plan the forest.

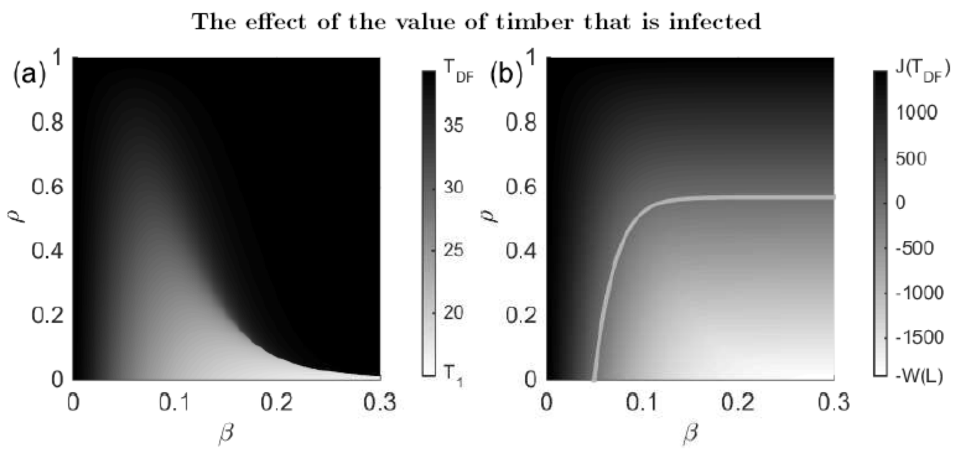

Figure 5: The effect of varying the value of timber from diseased trees relative to that from undiseased trees on the optimal rotation length. Variation in (a) optimal rotation length and (b) maximum NPV with the disease transmission coefficient, β, and relative revenue from timber that is infected, ρ. The grey scale on the right-hand side of both plots indicates the optimal rotation length (in years) and maximum NPV (in £) respectively. The grey curve in (b) highlights where the NPV is zero. The external pressure is at the baseline value (Table 2) and economic and ecological parameters can be found in Table 1.

FIGURE 3: TAKEN FROM MACPHERSON ET AL.

Another aspect of disease management from the viewpoint of the forest owner, is that there may be considerable uncertainty about how fast the disease will spread, particularly for novel diseases. Moreover, forest managers might learn more about the effects of the disease, or how it spreads, as time passes. This means it might be beneficial to "wait and see" what to do about a disease risk, as waiting enables learning. However, some of the actions which managers can take in response to a disease, such as clear-felling, are impossible or very costly to reverse. This means managers might undertake a control option which they later come to realise was not the correct choice. In such a setting (uncertainty, irreversibility), real options theory can be used to provide insight into how best to respond.

Dangerfield et al. use real options theory to analyse how forest managers should respond to a pest or disease risk when their options are characterized by uncertainty, learning and irreversibility. The main decision they consider is when the forest manager should act to control the disease, or how long they should wait. To incorporate uncertainty into the decision making process, the progress in the level of infection is described by a stochastic process. Epidemiological modelling is a convenient approach for determining the form of such a stochastic process since it describes the evolution in the level of infection within a host species based on the characteristics of disease spread. Furthermore, epidemiological modelling frameworks are well established and have become an important tool in understanding the invasion and persistence of pathogens. Dangerfield et al. look at the implications of different ways of specifying the stochastic spread of the disease via such epidemiological modelling. A control option (such as clear felling the forest) can be exercised at any time, but is irreversible. Simulation is used to investigate how the threshold value (when it is best to apply the treatment rather than wait any longer) depends on the nature of future uncertainty about the disease spread, and on the degree of volatility in the stochastic process. They show that using an inappropriate stochastic process to describe future uncertainty in the level of infection can lead to sub-optimal timing of control measures. Figure 4 below shows some of their results, expressed in terms of the proportion of the crop infected at which it is best to intervene. The authors also highlight the importance of the value taken by the discount rate, relative to the parameters which describe the stochastic process of disease spread, and thus the need to consider economic and epidemiological factors simultaneously.

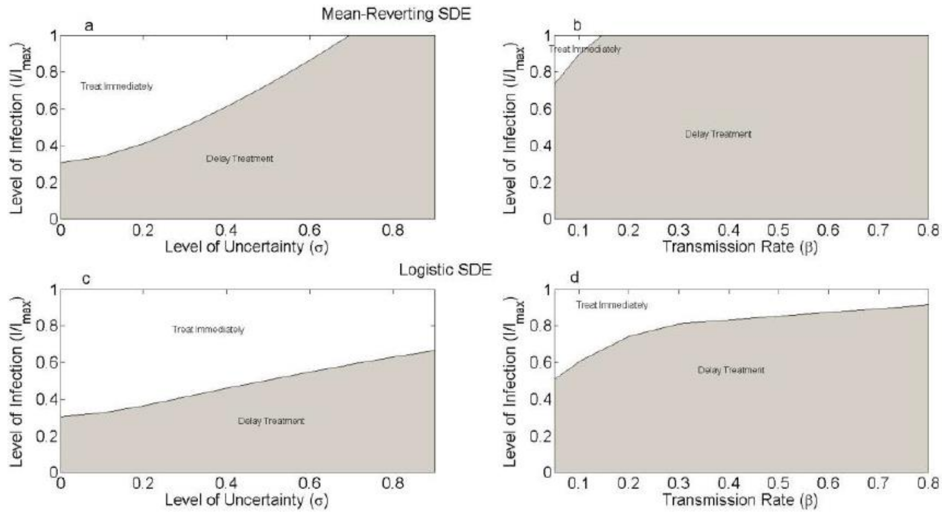

Figure 3: Policy plots showing the region in which treatment should be applied immediately and where treatment should be delayed for the mean-reverting SDE ((a) and (b)) and the logistic SDE ((c) and (d)) for different levels of uncertainty ((a) and (c)) and transmission rates ((b) and (d)). Other parameter values are given in Table 2.

FIGURE 4: TAKEN FROM DANGERFIELD ET AL.

SPATIAL CONSIDERATIONS

Diseases move between farms and between forests, and from one municipality or country to its neighbour. Actions by a specific municipality, say, to control the disease's spread will have benefits and costs to its neighbours; whilst there may be variations in the costs of the disease between neighbours (e.g. according to how big an area of susceptible crop they have). Charles Sims and co-authors analyse aspects of this spatial management problem, and specifically when it is best for a neighbour to "take one for the team". Again, they think about the issue of the value of waiting to act on a disease or bioinvasion, since this increases opportunities for learning. One can also contrast the nature of costs and benefits of taking preventative/mitigating actions at different time periods in terms of private and social costs. Indeed the value of waiting will not usually be the same for private and public choices. This is why it might be best, from a social optimality viewpoint, for a private agent (or one municipality) to wait longer than they would choose to wait from a purely private benefits viewpoint, and thus “take one for the team”.

In their example, disease or bioinvasion spreads along a corridor. Different agents (different municipalities, say) own different blocks or areas along this corridor. Each agent gets to decide when and whether they should take a costly action to slow the spread of the disease. As time goes forward, each agent learns more about how costly the disease will be to them in the future, but at the cost of allowing the disease to spread. Comparing the best time for a mitigating action to be taken under private versus collective considerations, shows that individual agents will ignore the benefits of their actions over time to other agents: these benefits include the value of information which others obtain from each agent waiting longer to undertake mitigation in their part of the corridor. Whether each agent chooses to act too soon or too late from the viewpoint of the collective’s best interests depends on the magnitude of uncertainty about the spread of the disease. This raises the possibility that the collective would wish the first agent in the corridor to take actions later than they would privately choose to do, if uncertainty about the disease is high.

DISEASES WHICH MOVE BETWEEN WILD ANIMALS AND FARM LIVESTOCK

An interesting economic question is how best to jointly manage wild animal populations and farm animals when both suffer from the same disease, and when the disease can move between these two populations. Bovine TB and Asian bird blue are two examples of such diseases. Horan et al. consider how many dollars should be invested in biosecurity measures which protect wild animal populations when diseases spread between wild and domesticated animals, due for example to farm animal movements linked to trade. Their model integrates disease dynamics in wild animals with production and trade of farmed animals. Trade here is from “breeders” of cattle to “finishers” of cattle, who live in two different regions. Breeding cattle can pass the disease onto wild animals, but wild animals can also infect these breeding cattle. Clearly, the rate at which wild animals can pass the disease to cattle and vice versa is important. Cattle have market values for breeders and finishers, whilst the social planner recognises the non-market economic value of wildlife.

Biosecurity measures can reduce transmission to wildlife populations, and Horan et al. found that the extent to which undertaking such measures is optimal does not depend on whether cattle are traded. However, the level of trading depends on the rate and degree of infection between the wild and farmed animal populations.

WHAT SHOULD BE DONE BEFORE THE DISEASE GETS HERE?

David Finnoff and co-authors focus on the effects of multiple possible equilibria in ex post outcomes on what is best to do ex ante, before the disease “arrives”. A non-convex system with multiple equilibria means that the best choice of ex spot decision will typically depend on the starting condition of the system. Thus, pre-infection choices also impact the ex post outcome. FInnoff et al. focus on the management of stock of a wild population prior to the disease arriving. Economic benefits come from harvesting individuals from the stock (both healthy and ill animals can be harvested, but only healthy animals have economic value). The health status of the animal is only known after it is harvested. The population density of the wild animal stock ex ante determines the size of the invasion if the invasion occurs. Ex ante, costly prevention effort can be expended to reduce the chance of the pathogen being introduced. Some complex analysis brings the conclusion that, under such conditions of uncertainty and non-convexity (multiple equilibria) ex post, the best management strategy ex ante before the pathogen arrives and becomes established is also not unique. Depending on circumstances, it may be better to focus on trying hard to reduce the costs of an invasion once it occurs, rather than trying to stop the invasion happening in the first place.

HUMAN RESPONSES TO DISEASE RISK AND POLICY

The economic benefits and costs of diseases are influenced by how people respond to disease risk and disease policy. Fenichel and co-authors use time-use data to investigate the cost-effectiveness and optimality of school closures during an outbreak of a flu-like virus in people (many such viruses are zoonotic). They find school closures can be cost-effective and even optimal depending on how people respond to disease and the policy. This work highlights the importance of costs avoided through substitution behaviour, but also the potential for disease mitigation strategies to underperform because of the human behavioural response to disease and policy. Economic behavioural feedbacks are important to consider when considering benefits and costs of disease management strategies.

CONCLUSIONS: WHAT CAN WE LEARN FROM ECONOMICS?

- Disease management should not only consider the epidemiology, but also the economics. Without doing so, management strategies are unlikely to be optimal, and may even be counterproductive, due to the interaction these factors have with each other. For example, deploying a control costs money, but may have a benefit in, say, reduced infection, thus there is a clear feedback between the control costs (economics) and the disease progress (epidemiology).
- Current management decisions and strategies used in absence of disease, can be affected if disease arises. Bioeconomic modelling can be used to examine how these strategies can be adapted to incorporate the effect of disease. However, trade-offs can often arise, for example waiting for a crop to grow at the possible cost of disease spreading further. Accurate formulation of economic, epidemiological and ecological factors can help understand the sensitivity to such trade-offs.
- Disease management strategies should consider the level(s) of uncertainty within the system as this can have a large impact on the deployment of a control.
- When an outbreak spans many agents, it is important to consider how individual actions lead to the collective outcomes since an individual's actions will affect neighbouring agents. What individuals choose in their private best interest will likely differ from an optimal strategy formulated assuming a collaborative effort. For example, it has been shown that it may be optimal for the agent who experiences the outbreak first, to wait longer than they would privately to take a risk reduction measure. This enables the collective can learn more. Policy needs to take private responses into account.
- The movement of livestock has often been considered a key driver of the spread of disease to wildlife populations. Thus considering livestock *and* wildlife is important when making a decision which affects the probability of disease transmission to wildlife, for example whether to apply biosecurity measures, trade livestock, or deploy trade regulations. Recent work has shown that whilst biosecurity measures prevent off-farm transmission to wildlife, the choice and level of biosecurity does not depend just on whether livestock are traded.
- Decisions on whether to prevent an invasion from arriving or to contain the invasion once it has arrived, often depend on forecasted management, which entails a degree of uncertainty in invasion probability and its magnitude. Using bioeconomic models can weigh up costs and benefits of prevention versus containment, and highlight how uncertainty interacts with the optimal solution. It has been shown that under certain conditions invasion prevention is optimal (although if any invasion did occur the outcome would be 'bad'), however, when the likelihood of invasion was increased, it may be optimal to attempt to contain the invasion.

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NOTES:

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