Beyond the Biosecurity Horizon

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Abstract

The dynamic process of market globalisation dictates that biological, technological and institutional changes have the capacity to alter the way in which future biosecurity policies are formulated and endorsed. This paper proposes a method of carrying out biosecurity risk profiling for the United Kingdom by comparing agricultural pest incursions under present circumstances with those under future conditions. Changing economic, environmental, social and political climates are set to alter the circumstances of future pest and disease incursions. With this in mind, this paper suggests a means of identifying responsible biosecurity risk management strategies for an uncertain future.

1. Introduction

The task for economists advising on an appropriate investment in biosecurity is a truly challenging one. A typical approach to assessing the significance of a pest involves a combination of intricate epidemiological models with a small number of hypothetical entry scenarios, and an estimated cost of successful eradication of the pest populations within these scenarios (e.g. Bhati and

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Rees 1996). However, this notion of *biosecurity significance* is both conceptually ambiguous and constantly changing. Not only are the agricultural industries potentially playing host to pest organisms dynamic, so too are pest entry pathways such as trade, tourism and mail. Climatic conditions are changing, as is the structure of the global market for agricultural goods with the formation of trade alliances, falling rates of subsidisation and the entry of developing countries into markets. All of these factors have the ability to affect the economic impact of a pest outbreak in the future.

With this in mind, this paper presents an alternative analytical framework that can be used in biosecurity risk management by indicating the strategic merit of targeting specific pest species based on a present and possible future *naturalisation*. This involves simulating the entry and spread of an agricultural pest in Britain under current invasion conditions, and comparing this to the likely circumstances the same pest might face if invasion were to take place in 20 years time. If the damage to host agricultural industries anticipated from naturalisation under present circumstances is greater than is expected in future, the biosecurity significance of the organism concerned is falling over time. On the other hand, if the reverse is true it indicates that there could be relatively increasing returns to investment in biosecurity efforts directed against the organism. This provides an important supplement to the overall magnitude of risk and the relative significance of other biosecurity threats when deciding how to allocate scarce biosecurity resources.

The structure of the paper is as follows. Section 2 outlines a model for measuring the biosecurity significance of pest species. This model is used in Section 3 to demonstrate how the expected damage from an insect pest, the Beet Leafhopper, can change as the circumstances of invasion change. Section 4 raises some complications associated with the modelling framework, and offers a solution through the application of a semi-quantitative multi-criteria approach. Conclusions are presented in Section 5.

2. The Model

Biological risk analysis techniques require a capacity for anticipating and estimating the impact of changes to factors that will affect future biological invasions. The specifications for a generic analytical framework appropriate for such a task are complex, particularly in terms of an epidemiological model. Firstly, it needs to capture the principle ecological processes such as arrival, establishment, population growth and spatial spread. Secondly, it must be generally applicable to a range of taxa, including animal and plant diseases, invertebrates, plants and vertebrates. And finally it must be able to integrate with an economic impact assessment approach that determines the ‘on-farm’ and downstream cost (including non-market costs) and revenue implications of pest naturalisation.

The process leading to a pest naturalisation that must be captured in a biological model is complex. It must involve the probability of entry and establishment to the region concerned, reproduction and area spread, the density of population within that area, and the development of sporadic *satellite* sites.

In order to begin populating an area, the first hurdle the pest must overcome is to arrive successfully, be it using natural or artificial means. Not only that, but it must arrive in sufficient numbers and in an area where it can survive and reproduce. The probability of such an occurrence is often small, but positive nonetheless. Formally, the probability of entry and establishment of pest *i* can be expressed as the product of the probability of entry in a region (p_{ent}) and the probability of establishment within that region (p_{est}), i.e.:

$$P_i = p_{ent} \times p_{est} \quad \text{where} \quad 0 < P_i < 1 \tag{1}$$

What follows the successful entry and establishment of a pest largely determines its economic significance. To reiterate, the assumption here is that once a pest becomes established it becomes naturalised, spreading to the extent dictated by biological and ecological circumstances[1].

Other economic assumptions in the following conceptual discussion are that there is one pest organism of concern that is exotic to a particular country or region, and that this pest has one known host which happens to be a commercial agricultural industry in a homogenous environment. Secondly,

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[1] In effect, this assumes that agricultural industries receive no assistance from public institutions, and that the risk of pest incursions is simply a risky production parameter. Once again, it is not suggested that such a situation will eventuate, but it is necessary to determine what the true benefits to agriculturalists are from maintaining pest area freedoms, and therefore how much effort should be expended on their maintenance.

assume the domestic market for the potentially affected commodity is perfectly competitive, implying product homogeneity. Thirdly, assume that the contribution of domestic producers of that affected commodity to the total world supply is insufficient to exert influence on the world price, the exchange rate and domestic markets for other commodities. Finally, assume society has a neutral attitude to pest risk[2]. On this basis there are three economic parameters used in determining pest-induced producer surplus losses:

1. Total management cost increments – Production cost increases will result from the need for additional pest management activities necessary to minimise crop/livestock damage. Depending on the nature of the pest concerned this may involve chemical applications (including additional vehicle and labour costs), the destruction of infected/infested hosts, habitat manipulation and/or biological control techniques[3].

2. Revenue losses – This will comprise firstly of a direct loss of marketable product. Despite incorporating a pest control program into normal management practice, a certain amount of yield loss may still occur through the effects of an introduced pest. This effect may be as high as

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[2] This is a big assumption that is not explored here. It may be more likely that society is risk averse when it comes to animal diseases, and many crop pests. It may be risk neutral on broader environmental risks from invasives, or maybe even risk taking, albeit unwittingly.

[3] No attempt is made to predict the development and availability of new and improved control agents for resistant pests, the likely cost of these products and the capacity of pest species to develop resistance to them.

100 per cent in some cases, while in others it may be negligible. Secondly, revenue losses include the loss of export sales. In many cases the loss of pest-freedom status can have a profound impact on export revenue since the ability to sell products to markets around the world is compromised. This does not necessarily mean that all exports of an affected commodity are lost[4]. Although high-priced markets may be lost, the good can often be sold to 'second-best' markets where a lower price is received. The subsequent loss of earnings represents a cost associated with a pest's naturalisation.

3. 'Flow-on' effects - Due to their use as inputs into the production processes of other industries, changing production environments for agricultural goods can have indirect as well as direct consequences. If these indirect effects are taken into account the impact of agricultural pests can be far greater than indicated by primary production losses. Consequential flow-on effects from exogenous supply shocks may be captured using input-output tables, but are ignored here. Flow-on effects also include environmental damage sustained through pest damage, but these too are temporarily ignored in this theoretical discussion, recalling the assumption above concerning host specificity.

The total area affected is the sum of a number of 'sites', of which there are an *original* and *satellites*. Total *expected* damage cost of an original site in time period t (ED_t)

[4] e.g. Continued US beef exports to EU countries after the BSE cases in Washington State.

$$\mathrm{ED}_t = P_i \times (MDC_i \times N_t \times A_t) \qquad (2)$$

where:

$$MDC_i = \text{marginal damage cost pest } i;$$
$$N_t = \text{pest density at time } t;$$
$$A_t = \text{area affected at time } t;$$

Here, the average total cost increment and total revenue loss comprises of the factors explained above, i.e.:

$$MDC_i = \Delta C_i + \Delta R_i \qquad (3)$$

where:

$$\Delta C_i = \text{increase in average total cost of production attributable to pest } i;$$
$$\Delta R_i = \text{decrease in total revenue attributable to pest } i.$$

A constant marginal damage cost (or average damage cost) is assumed that can then be combined with a biological spread model.

Once established in the original site, a pest begins dispersing. The way in which it does so depends on the organism concerned. Since this is intended as a generic framework, a relatively simple method of modelling dispersal is called for. Once established, we assume that the area occupied by the pest increases with time (Hengeweld, 1989; Lewis 1997):

$$A_t = 4D\pi r t^2 \qquad (4)$$

where:

D = population diffusion coefficient;
r = intrinsic rate of population growth;
t = time since establishment.

Thus, a homogenous environment and equal expansion rate in each direction from the initial point of spread is assumed. Equation (4) is a generic and relatively robust result for asymptotic expansion derived from reaction-diffusion (e.g. Fisher, 1937) models of the form:

$$\frac{dn}{dt} = f(n) + D\left(\frac{d^2 n}{dx^2} + \frac{d^2 n}{dy^2}\right) \tag{5}$$

where:

$f(n)$ = per capita growth rate.

Equation (4) is convenient as r can be derived from published studies of population growth (e.g. Shigesada and Kawasaki 1997) and D can be derived from the Mean Dispersal Distance (MDD) (Andow *et al*, 1990):

$$\text{i.e. } D = \frac{2MDD^2}{\pi} \tag{6}$$

Area alone is not sufficient for the purposes of an economic impact assessment since the density of the pest population within that area influences the control measures employed by affected farmers to counter the impacts of the pest. The model assumes that in each unit of area occupied by the expanding population, the local population density N grows logistically to the carrying capacity of the environment K, such that:

$$N = \frac{K}{1 + \left(\frac{K}{N_{\min}} - 1 \right) e^{-rt}} \quad (7)$$

where:

$N_{\min}$ = size of the original pest influx.

As the area involved in an initial site expansion and the population density within that area increases, so too does the likelihood of a random satellite outbreak some distance from the original site:

$$P_{sat} = \mu A \quad (8)$$

where:

μ = intrinsic rate of new foci generation, and
A = total area occupied by original population prior to satellites.

Satellite populations grow and expand in the same manner as the original population. Total occupied area of the original site and satellites grows until $A = A_{\max}$ (maximum habitable area), at which point total area remains constant.

This relatively simple model allows both biological and economic parameters to be brought together to examine the quarantine significance of pest organisms, and how they are likely to change over time. In this sense it represents a risk management framework intended as a policy guide. If the model can clearly demonstrate pests of high and low expected damage, and those likely to be of increasing, decreasing and constant economic significance over time, it will provide a valuable decision-making aid to policy-makers faced with the prospect of providing the highest social benefit with limited biosecurity resources.

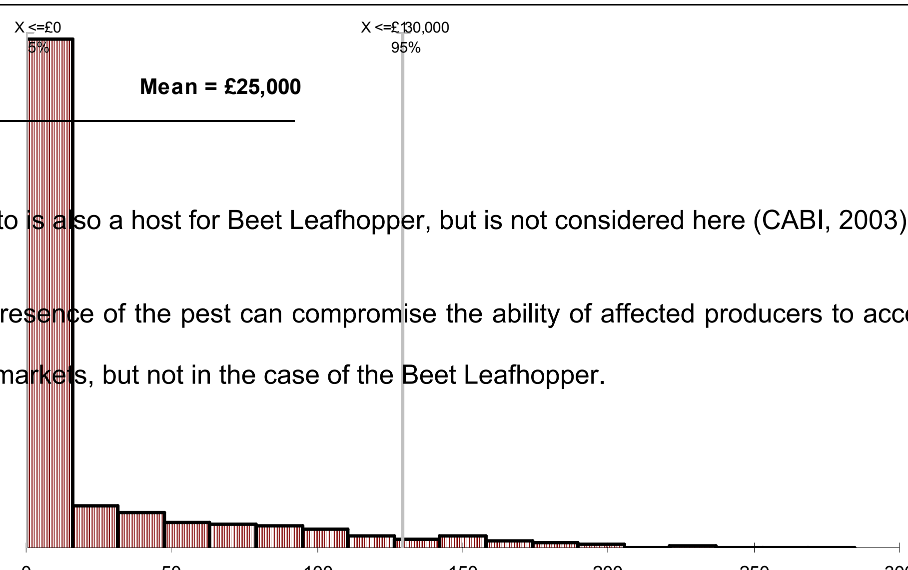
3. Numerical Illustration

The model described in section 2 is to be used to compare a control case with future scenarios to examine how the likely significance of pests may change over time. The control case is to be formed on the basis of circumstances that would characterise an outbreak/incursion at present, while a scenario describes possible future circumstances. While there are an infinite number of possible scenarios that may transpire in the next twenty years or so, there are (arguably) a limited number of topical issues of academic and social interest. Perhaps the most prominent ones involve the possible effects of global warming, changes in land use, and the reduction of agricultural subsidisation. Using the model of section 3, the *broad* ramifications of each can be explored.

Again, by comparing a control case with these possible future scenarios, the model is able to indicate if the strategic significance of a pest species (from a biosecurity policy perspective) is set to increase, decrease, or remain constant over time. In particular, a policy-maker seeking to achieve relatively high future social benefits accruing from resource allocations in the present is provided with an indication of those threats that present a growing risk, and those that may be negated through exogenous circumstance. The model is therefore able to help manage biosecurity risk in a socially desirable fashion by setting priorities and improving the effectiveness and efficiency of policy decisions through a better understanding of potential threats.

This can be demonstrated using an example of an exotic insect pest of sugar beet, the Beet Leafhopper (*Neoaliturus tenellus*)[5]. The annual gross value of the sugar beet crop in Britain is around £309.6 million, occupying some 169,000 hectares (DEFRA, 2002). Although not present in Britain, Beet Leafhopper is currently found throughout Asia, Africa and North America, as well as parts of Europe (including France, Italy and Spain) (CABI, 2003). If naturalised in Britain, the effects are twofold. Firstly, the average total cost of sugar beet production would rise in response to the need for additional chemical, labour and machinery costs. Secondly, the average total revenue of affected farms will fall due to yield loss.[6] In this example, neither of these effects are particularly large.

Assume the parameters describing the possible naturalisation of Beet Leafhopper in the control case produce the expected damage estimate illustrated in Figure 1. Here, multiple iterations of the spread model have been used to form a distribution of likely costs attributable to the insect over a 20-year period. The mean expected annual damage is £25,000, which indicates this pest is not a severe threat to the British economy in the control



[5] Tomato is also a host for Beet Leafhopper, but is not considered here (CABI, 2003).

[6] The presence of the pest can compromise the ability of affected producers to access world export markets, but not in the case of the Beet Leafhopper.

Figure 1: The Average Annual Expected Damage Attributable to the Beet Leafhopper in the Control Case.

case. However, a biosecurity policy-maker is interested in whether this will remain so as economic and ecological conditions change.

In demonstrating how the model is able to explain this, assume initially there is one future scenario of interest where the probability of Beet Leafhopper entry and establishment increases over time. For example, the probability of entry may rise as the volume of imports entering Britain through Felixstowe rises as the port lies in close proximity to beet crops. The probability of establishment might increase as a result of climate change making Britain a more suitable habitat for the insect. If this scenario is simulated simultaneously with the control case, it is likely that the corresponding average area infested by the insect over time will be higher in the scenario since the likelihood of an outbreak is higher, as illustrated in Figure 2. Hence, the pest's biosecurity significance is set to rise over time.

By using multiple iterations of both the control case and scenario and comparing the two, a distribution of the expected damage differential is

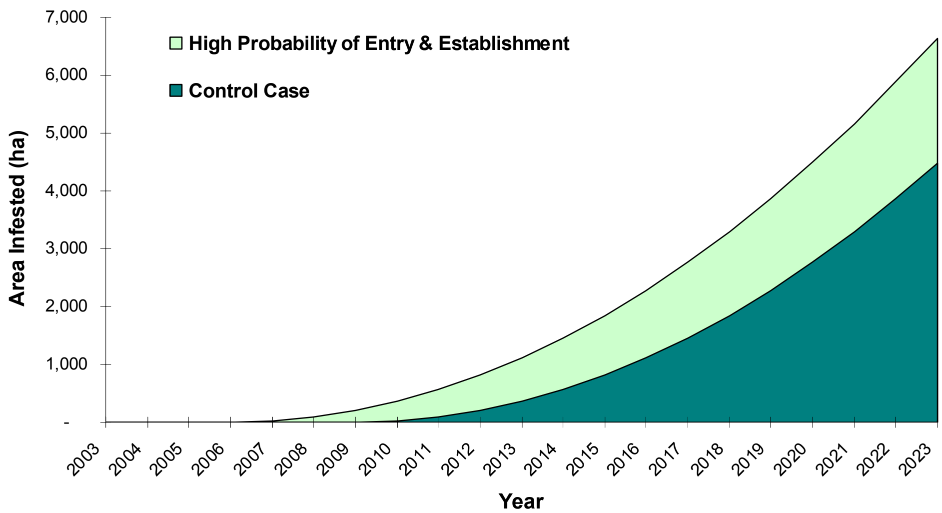


Figure 2: Changes in the Strategic Significance of a Pest

formed. If the economic and ecological circumstances of a future Beet Leafhopper outbreak are expected to resemble those of the scenario, this differential provides a numerical representation of the resultant change in biosecurity significance. Figure 3 shows how a higher probability of entry and establishment increases the expected damage from the insect over time.

Now assume a second scenario is of interest to biosecurity policy-makers that involves the gross value of the sugar beet industry declining over time. This situation could result from Common Agricultural Policy reform exposing domestic producers to greater international competition. If this occurs, the strategic significance of sugar beet pests like the Beet Leafhopper may fall over time. In effect, the capacity of such pests to cause economic damage declines as the size of their host industry falls, as demonstrated in Figure 4.

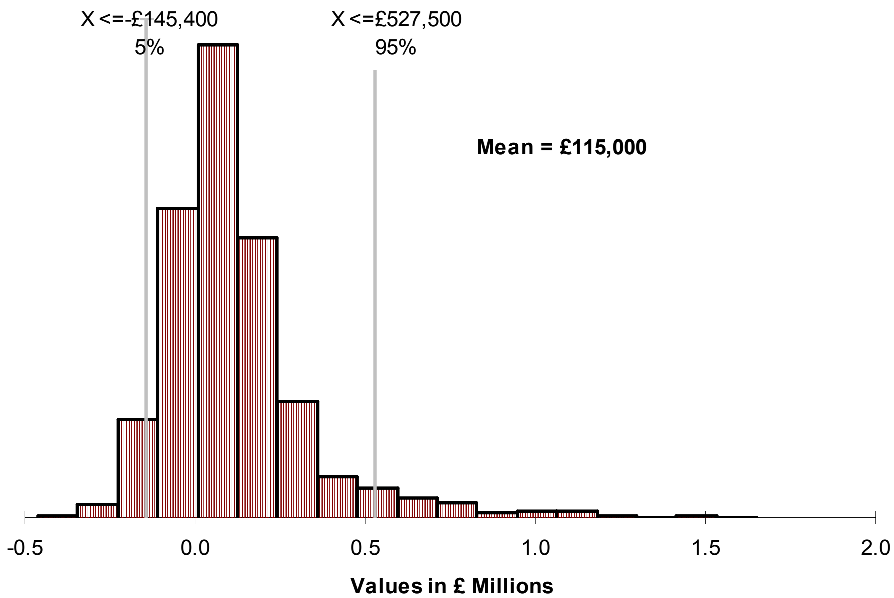


Figure 3: Expected Damage Differential – Higher Probability of Entry and Establishment

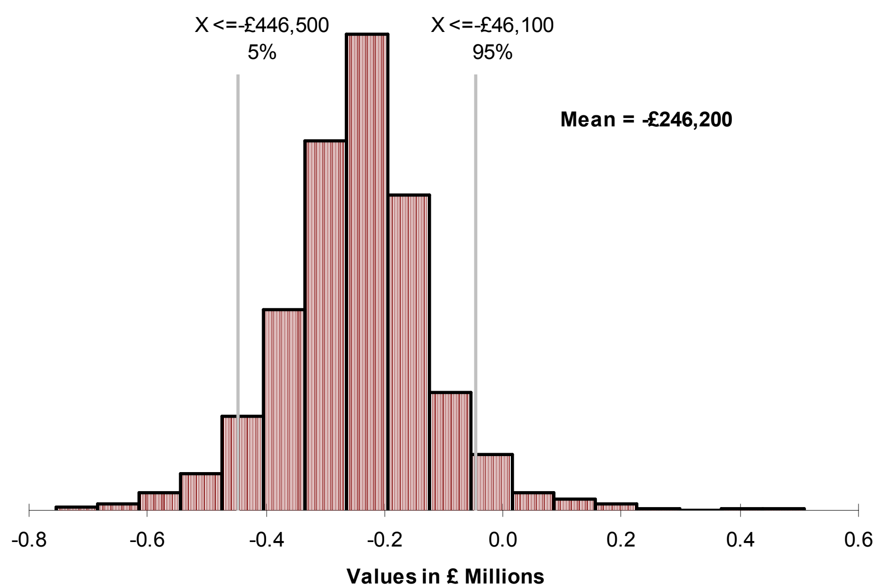


Figure 4: Expected Damage Differential – CAP Reform

4. Dealing With Complexities

4.1 Risk and Parameterisation

When attempting to model any biological system, the uncertainty and variability inherent in many parameter values can not be ignored[7]. Using point estimates of the parameters does not do justice to the highly complex nature of interspecies interactions, seasonality and evolution. Therefore, a system of semi-quantitative categorisation can be used to parameterise the model. This simple process requires relevant experts to choose from a set of alternatives to indicate that which best describes a model parameter pertaining to a particular pest. This alternative effectively describes a probability distribution that can then be used in Monte Carlo simulation.

[7] Natural *variability* reflects the heterogeneity of a parameter, and can not be eliminated by continued sampling. For instance, one could sample 100 different hectares of crop infested with a pest in an effort to estimate N_{max} and receive 100 different estimates. *Uncertainty*, on the other hand, can be reduced by increased sampling since it is caused through a lack of data or sampling errors. For instance, the uncertainty surrounding the number of additional chemical applications per season applied by farmers in response to the pest becoming established in their crop would be higher if 10 farmers were surveyed than if 100 farmers were surveyed.

For instance, take the probability of pest entry, p_{ent}. Although an economic analysis of a potential agricultural pest threat could be accompanied by a comprehensive risk analysis designed to determine likely probabilities of entry (and establishment for that matter), this is not always possible. An alternative is presented in Table 1. Here, the p_{ent} in both the base case and scenarios are estimated using the semi-quantitative risk categorisation methodology outlined in AFFA (2001), presented in table 1.

Consider once more the example of the Beet Leafhopper. Britain does not import sugar beet from areas where it is established, and is located a reasonable distance from known populations. However, it does import tomatoes from Europe (DEFRA, 2002). So, the likelihood of entry into Britain can not be considered negligible, but may be *Very Low*. As Table 1 indicates, this would mean an entry probability (in the control case) of between 0.001 and 0.05, which can be specified quantitatively as a uniform distribution for modelling purposes. If a consensus of relevant trade, climate and ecological experts believed that trade liberalization will open up new and efficient pathways for Beet Leafhopper to travel to Britain, the likelihood of it entering might be re-categorised as *Moderate*. The impact of this scenario can be

Table 1: Semi-Quantifiable Risk Categorisation Methodology (AFFA, 2001)

Likelihood	Descriptive Definition	Probability Range
High	Very likely to occur	0.7 - 1.0
Moderate	Occurs with even probability	0.3 - 0.7
Low	Unlikely to occur	0.05 - 0.3
Very Low	Very unlikely to occur	0.001 - 0.05

Extremely Low	Extremely unlikely to occur	0.000001 - 0.001
Negligible	Almost certainly will not occur	0 - 0.000001

estimated using the corresponding Uniform distribution with a minimum value of 0.3 and a maximum of 0.7. So by using the model to compare the control case and the scenario it is possible to demonstrate the extent to which the Beat Leafhopper's biosecurity significance is set to rise over time.

4.2 Environmental Considerations

Biosecurity policies have the potential to protect not only cultivated crops from invasive pests, but also native ecosystems that might become hosts to pests and diseases in the event of an incursion. But, placing an economic value on this protection is highly problematic, and often prevents their inclusion in economic analyses of quarantine strategies. It would therefore seem imperative to provide a cost-effective mechanism to present both market and non-market effects of invasive pests in comparable ways.

There are numerous environmental factors that may cause non-indigenous species to become abundant and persistent when introduced to new areas, some of which include:

- a lack of natural predation regulating pest populations;
- an abundance of native species that have not evolved suitable defence mechanisms against alien predatory species;

- the creation of artificial habitats such as cultivated crops and grazing areas that provide favourable ecosystems for exotic pests; and
- the ability of some alien species to adapt to new environments and develop new relationships with host species (Pimentel *et al*, 2000).

Where circumstances like these apply severe damage can be inflicted upon native ecosystems, which may or may not be reversible.

While it is relatively straightforward to cite the biological causes of pest population explosions, the task of assigning economic values to environmental losses caused as a result is not. When compared to agricultural commodities with a market-based annual value, a market for the natural environment does not exist. Moreover, not only may it (or its components) have a non-market value in terms of use, it may also have existence, bequest or moral values which are dependant on its continued existence, and which could extend over generations in time (Mumford, 2001).

In addition to this valuation issue, environmental damage takes place in a very different ecological setting to agricultural damage. Generally, invasive organisms face a more difficult challenge becoming established in relatively stable, diverse ecosystems in which competition for life-sustaining resources is fierce. Consequently, explosive growth and spread for environmental invasions tends to be less common than for agricultural pests. Furthermore, new invaders may be less conspicuous in a species-diverse context. Small changes in one, widely distributed species tends to escape public attention, and will only create concern as the number of patches of ecosystem under threat begin to noticeably diminish. The irreplaceability or substitutability of that environment will determine the extent of public concern aroused by its depletion or deprivation.

4.3 Solution and Pest Prioritisation

The approach to modelling the impacts of invasive pests outlined above allows the biosecurity threats facing Britain to be evaluated in a straightforward, *consistent* manner. The framework therefore enables a systematic threat prioritisation, whereby species can be compared in a common format. Moreover, in the assessment of each pest, it may be practical for risk management decision-making if the information produced is semi-quantitative (and in some cases qualitative). This is particularly true where quantitative measures of introduction frequencies, market and non-market impacts are difficult to form as a raft of complex information can be described using simple measures of severity.

This development extends to the inclusion of non-market information. By converting expected damage cost (describing the loss of agricultural crops attributable to pest naturalisation), probability of entry and establishment and non-market information into a set of alternatives, they can then be ranked for each individual pest. Using such a system in conjunction with scenario analysis, a policy-maker is potentially placed in the position where they are able to identify high-return areas of investment for scarce biosecurity resources.

To demonstrate, assume a simple system of categorisation is used whereby expected damage, probability of entry and establishment and non-market effects are "scored" as High, Medium or Low (i.e. 1 – 3). Further assume there are three pests of concern, A, B and C, and that scenarios expected to characterise future invasions are X, Y and Z. There is also a control case where the circumstances surrounding an invasion represent those of the present. The information concerning economic, probabilistic and non-market implications of pest introductions can be combined in an *Impact Table*, an example of which is provided by Table 2.

By integrating all available information, the framework clearly and transparently indicates the relative merits of targeting individual species at a policy level given "different states of the world". Simply adding the scores nominated to each pest enables them to be ranked in order of severity (or strategic significance) for each scenario.

i.e.	Control Case	A = B = C
	X	B < C < A
	Y	A < B < C
	Z	C < A < B.

Table 2: Impact Table

Scenario	Pest	Expected Damage	Probability of Entry & Establishment	Non-Market Cost	Score
Control Case	A	High - 3	Low - 1	Medium - 2	6
	B	High - 3	Medium - 2	Low - 1	6
	C	Medium - 2	Medium - 2	Medium - 2	6
X	A	High - 3	Medium - 2	Medium - 2	7
	B	Low - 1	High - 3	Low - 1	5
	C	Medium - 2	Medium - 2	Medium - 2	6
Y	A	Low - 1	Low - 1	Medium - 2	4
	B	Medium - 2	Medium - 2	Low - 1	5
	C	High - 3	Medium - 2	Medium - 2	7
Z	A	High - 3	Low - 1	Medium - 2	6
	B	High - 3	High - 3	Low - 1	7
	C	Medium - 2	Low - 1	Medium - 2	5

In effect, it maps out directions for achieving the highest expected social gains from the investment of limited biosecurity resources under a range of possible circumstances[8].

[8] It may be the case that weights need to be attached to each of the criteria used to rank pests based on political imperatives.

5. Conclusions

This paper provides biosecurity policy-makers with a risk management decision-making framework that may be used to improve the returns to invested resources. By utilising information on the potential impact of pest naturalisation on agricultural commodities, society and the environment, it has developed a means by which pests can be assessed and ranked according to their strategic significance. In this way, investment areas expected to pay higher dividends in the future can be identified, and appropriate funding decisions made to reduce future pest impacts. The model presented can be broadly applied to many pests and diseases with a variety of impacts. Therefore, the model's strength is that it can inform a large number of biosecurity decisions concerning many and varied pest species. It is therefore suggested that applying this type of model to biosecurity policy decision-making procedures can improve biosecurity risk management strategies.

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