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Agricultural biosecurity

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The prevention and control of new pest and disease introductions is an agricultural challenge which is attracting growing public interest. This interest is in part driven by an impression that the threat is increasing, but there has been little analysis of the changing rates of biosecurity threat, and existing evidence is equivocal. Traditional biosecurity systems for animals and plants differ substantially but are beginning to converge. Bio-economic modelling of risk will be a valuable tool in guiding the allocation of limited resources for biosecurity. The future of prevention and management systems will be strongly influenced by new technology and the growing role of the private sector. Overall, today's biosecurity systems are challenged by changing national priorities regarding trade, by new concerns about environmental effects of biological invasions and by the question 'who pays?'. Tomorrow's systems may need to be quite different to be effective. We suggest three changes: an integration of plant and animal biosecurity around a common, proactive, risk-based approach; a greater focus on international cooperation to deal with threats at source; and a commitment to refocus biosecurity on building resilience to invasion into agroecosystems rather than building walls around them.

Keywords: biosecurity; agriculture; pest; disease; economics; risk

1. WHAT IS AGRICULTURAL BIOSECURITY?

Biosecurity is a term that has many interpretations. In this paper, biosecurity means the protection of countries against alien pests (insects, vertebrates, etc.) and diseases. Biosecurity has also been used to describe measures taken to reduce the risk of spread of animal disease on farms (Defra 2005*a*) and defence against biological weapons, such as the deliberate introduction of smallpox or anthrax into human populations (O'Toole & Inglesby 2003). FAO (2003) has adopted biosecurity as a holistic term which encompasses policy and regulation to protect agriculture, food and the environment from biological risk.

The rebranding of the centuries-old practice of battling agricultural pest and disease introductions as 'biosecurity' is itself interesting and reflects how current societal concerns about globalization and terrorism influence agriculture in new ways. As Josling *et al.* (2003) observe '…since the terrorist attacks on the World Trade Centre and the Pentagon on September 11, 2001… biosecurity has taken on new dimensions and products that move across borders are treated more suspiciously, [creating] uncertainty and transaction costs that impinge particularly on trade that could put domestic animal, plant or human populations at risk'.

Following a short survey of recent biosecurity threats, we examine and compare biosecurity systems for crops and livestock. We then explore whether threats to biosecurity are increasing and examine developments in the measurement of risk and in prevention and eradication of new threats. Finally, we explore major changes in today's biosecurity systems and make recommendations about building a more biosecure future for agriculture.

2. RECENT BIOSECURITY THREATS

Recent years have seen a range of biosecurity problems which are notable for their high costs and public profile. With respect to livestock, an outbreak of classic swine fever in 1997 cost The Netherlands approximately £2.4bn (Whiting 2003). The foot and mouth disease (FMD) outbreak in 2001 cost the UK approximately £7bn (Thompson *et al.* 2002), while the appearance of bovine spongiform encephalopathy (BSE) in Canada and the USA in 2003 is estimated to have cost each of those countries $3–4bn in lost trade revenue (Anon 2004). Until 2003, avian influenza had been considered a relatively rare animal disease, but in that year a devastating outbreak occurred in The Netherlands and a series of outbreaks began in Asia which have continued and spread to other regions (Harder & Werner 2006).

The explosive growth of aquaculture and mariculture worldwide has led to the spread of many serious diseases and parasites of fishes and shrimp (Hedrick 1996; Hill 2000). In Europe, the recent spread of *Gyrodactylus salaris*, a small, leech-like parasite of salmonids, threatens salmon fishing (Peeler *et al.* 2003). Insect pests of animals have also been moving worldwide. The introduction of the New World screwworm fly, *Cochliomyia hominivorax*, into Africa in 1988 led to a successful emergency eradication programme coordinated by the UN (Lindquist *et al.* 1992).

While accidental, human-assisted movement of pests and pathogens appears to be the major cause of animal biosecurity problems, other mechanisms of introduction are emerging. For instance, the spread of bluetongue disease of sheep in Europe appears to be related to range extension of its culicoid fly vectors (Defra 2002), probably as a result of climate change. The African bont tick, *Amblyomma variegatum*, a potential vector of important cattle diseases, was

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accidentally introduced into the Caribbean in the 1800s, but its rapid spread into new countries in recent decades has been stimulated by another introduction, that of the cattle egret, which spreads the tick to new island countries (Pegram *et al.* 2004).

The great diversity of crops and their rich and often cryptic insect and pathogen complexes guarantee a continuing and high level of new pest and disease introductions. In recent years, particularly worrying introductions have occurred on four crops: wheat, rice, maize and potatoes that constitute 50% of the world's food supply. Karnal bunt, *Tilletia indica*, an Asian fungal disease of wheat, was introduced into the US in 1996, where it is under containment in southwestern states (USDA 2004). Potato late blight, *Phytophthora infestans*, responsible for the Irish potato famine that led to the death or emigration of millions of rural poor in the mid-1800s, continues to evolve and spread new virulent forms (Goodwin *et al.* 1994). In East Africa, wheat stem rust, *Puccinia graminis*, has recently re-emerged after decades of suppression with resistant varieties, creating a global biosecurity risk if it now spreads (CIMMYT 2005).

In the UK, a booming trade in horticultural plants has led to many new introductions (Independent 2003) one of which, the fungus *Phytophthora ramorum*, may threaten indigenous forest trees (Brasier *et al.* 2004; Defra 2005*c*). Forestry in general has seen a dramatic pattern of new disease and pest introduction, particularly through the recent opening of trade between East Asia and other regions (Cock 2003).

This brief snapshot of agricultural biosecurity threats illustrates their diversity and considerable potential impact on agriculture. It also illustrates a policy-relevant phenomenon. Since biosecurity problems are usually one-off, distinctive, time-bound events, they tend to be presented as clusters of cases as above (see also Bright 1998; Baskin 2002). Taken all together, we may get the impression of an immense and urgent crisis. Further, discovery of one new threat can lead to greater surveillance which in turn increases the likelihood of finding another, creating a rising spiral of new problems. In fact, at a national level, truly new introductions may be relatively few and far between, while chronic, indigenous or long-established pest or disease problems may be of greater economic significance than those posed by new biosecurity threats. One of the challenges of biosecurity research is to move beyond anecdote into rigorous analysis of the nature and impact of these diverse threats in the proper context.

3. BIOSECURITY SYSTEMS

National plant and animal health systems seek to prevent the introductions of new pest or disease. Where this fails, eradication is an option if populations of the introduced species are still relatively small and local. If this is not successful, the alternative option may be to suppress populations on a long-term basis to minimize impact. Protecting national agriculture from new pests and diseases is generally considered to be a public good, because it promotes food security, and hence it is usually undertaken by governments, with the co-operation of importers, shippers and travellers (Mumford 2002). Where protection of agriculture has a more private than public good consequence, and few externalities, then it is more appropriately a private sector activity (Nugent *et al.* 2001). Hence, the cost of long-term control of established pests and diseases is usually borne by individual agricultural producers.

With a range of potential new pest threats, governments must prioritize where to put funds in prevention, eradication and control. The best predictors of the potential threat posed by a new pest or disease remain its impact on another country, its likelihood of spread and the value of the resource that could be affected in the new country, bearing in mind local climate and management conditions. This fact has fostered international exchange of information on agricultural pests and diseases and the establishment of inter-governmental biosecurity networks. For plants, these include the International Plant Protection Convention (IPPC), hosted by the Food and Agriculture Organization of the United Nations (FAO), associated regional plant protection organizations and various specific regional agreements. For animals, they include the Organization International des Epizooties (OIE) and FAO.

These international biosecurity systems develop and adopt standards which may be applied by authorities at a national level. Under OIE guidelines, countries have had to notify others about the appearance of any of 10 animal diseases, the A list, considered particularly capable of rapid spread and damage, and then must 'stamp out' these diseases to regain full international trading status. A second B list contains significant diseases which do not require this level of action. Hence, decisions about animal biosecurity are to a great extent pre-assigned to a reactive category based on the identity of the disease alone, not on the local circumstances.

For plant systems, national and international organizations have embraced a process of risk analysis, promoted by the IPPC, which includes estimation of the probability of introduction of a new pest or disease and the probable impact which it may have. Species deemed to be of high risk *in a particular situation* may then be targeted for active prevention or eradication in the event of their introduction. In Europe, such 'quarantine pest' status is determined by the EC's Plant Health Committee, following formal risk analysis (Defra 2005*b*). Quarantine pests are designated by international (in the case of the UK, regional EU) agreement. This follows a pest risk analysis, approved by the EC's Plant Health Committee.

Pest and disease problems of animals and plants have some profound epidemiological and economic similarities, similar prevention and control systems and similar drivers of risk, including trade and transport. Yet their biosecurity systems today exhibit some profound differences. Are these differences related to the biological nature of these different threats, or to the particular history of these biosecurity systems or both?

From a biological perspective, there are many more potential crop than livestock pests and diseases. Countries are more likely to share livestock species and hence key threats, while key crop species and threats will vary depending upon geography and climate. This makes a globally relevant shortlist of key crop threats unlikely, and favours local risk analysis as a means of identifying national priorities. Further, animals are more likely than plants to be moved in an infective stage into contagious, susceptible populations. Plants are often moved as seeds, eliminating all but seed-borne diseases and not directly into susceptible crops. If breaches of animal biosecurity are likely to be more sudden and dramatic, it might be argued that constant preparedness for quick reaction will be as or more effective than a process of situation-specific risk assessment.

However, there are also important economic and historical dimensions to the differences in animal and plant biosecurity. Relative to crops, animals are high-value investments, and perhaps for this reason their protection has been regulated by governments for centuries. Significantly, today's procedures for animal biosecurity, including isolation of diseased animals, quarantine and culling, were established in Europe for diseases such as anthrax, FMD, sheep pox and rinderpest between the fifteenth and eighteenth centuries (Blancou 2003). These measures pre-date, by one to several centuries, the actual discovery of the disease agent and its epidemiology. Further, these empirical, but highly effective practices have been maintained over the past two centuries by a socially powerful professional society of veterinarians.

Plant biosecurity, by contrast, has not enjoyed this degree of government attention or professional stewardship. Development of its methods has been much more recent and has been influenced by twentieth-century research into insect ecology and plant disease epidemiology, which has taken it down a predictive path based on risk assessment.

Today, with a better understanding of pest and disease ecology, we can see that animal and plant biosecurity threats are, in fact, very similar and that particular differences are not so much taxonomic but biological, relating to epidemiological parameters like R_0, the basic reproduction number which determines whether a disease is likely to spread (Woolhouse *et al.* 2005). Under a unifying, modern epidemiological framework, there is a real opportunity today to harmonize our approaches to animal and plant biosecurity. A more risk-based approach has merit for both systems in moving biosecurity from a reactive towards a proactive position which focuses more on prevention and anticipates better emergence of entirely new threats. Indeed, emphasis on prevention and proaction characterize Defra's recent Animal Health and Welfare Strategy (2004) and Plant Health Strategy (2005*c*). On an international level, OIE has recently modified its traditional A and B lists into a single list and included notification requirements alerting other countries not only to these species but also to other patterns of emerging disease with significant morbidity/mortality or zoonotic potential (OIE 2005). This continuum of assessment across disease threats also signifies a degree of convergence between animal and plant biosecurity systems around a risk-based, proactive approach.

4. A GROWING THREAT?

There is a broad consensus that biosecurity problems are getting worse owing to globalization, and specifically owing to growing trade, travel, transportation and tourism, the 'four Ts'. Is this true? Recent 'clusters' of biosecurity problems, as highlighted in §1 have certainly given an impression of a growing problem. A useful analogy may be drawn here with climate change, where a recent pattern of unusually warm years has helped the public to accept the concept of climate change. The convincing evidence for climate change, however, lies not in this experience, but in the scientific analysis of long-term climatic trends. The same will be true for biosecurity threats, that is, we need to evaluate the evidence for a change in threat over time and in doing so, identify the probable causes of this change.

Despite the fact that we have national systems which record interceptions and outbreaks, there has been little research to date into the pattern of introduction of new pests and diseases, which might test this hypothesis that the biosecurity threat is growing (Everett 2000; Waage *et al.* 2005*a*,*b*). Even with a constant or decreasing rate of introduction, a biosecurity 'burden' of new pests and diseases will accumulate and, in this sense, the problem will always 'get worse'. And of course, with demonstrably growing world trade in relevant agricultural commodities (Josling *et al.* 2003), a correlation of this growing burden with growing trade is easily obtained, but may provide little evidence of causation.

A first step therefore is to refine our hypothesis, to explore whether the *rate* of introduction or establishment of new pests and disease is rising as a result of global changes. Here we will use *introduction* to describe the arrival of a species in a country, which may be detected by interception at ports or local outbreaks, while *establishment* means that the species has reproducing, continuing populations in the country. In this survey, we have concentrated on plant pests and diseases for which there is the best evidence, perhaps owing to the sheer number of potential new species arriving at borders.

Studies of annual interceptions of non-native arthropod species at US ports from 1990 to 1999 suggest an increasing trend (National Research Council 2002), while new pest and disease outbreaks recorded by Defra in the UK fluctuate approximately 150 from 1993 to 2000 and then jump to 350 in 2002 (National Audit Office 2003). Analysis of interception records is complicated by the fact that reporting will increase with inspection effort and focus on particular pathways. Work *et al.* (2005) have demonstrated the positive relationship between levels of inspections and numbers of insect species recently intercepted at US ports, while Clarke (2004) relates the observation that interceptions of pests and diseases on Australian timber imports jumped following policy recommendations to tighten quarantine. Thus, we may be finding more because we are looking harder or in the right places. New, integrated reporting systems which account for effort should provide better opportunities for analysis of interception data in future.

Records of introduction will be affected in an opposite manner by the improvement in pre-importation prevention measures. Again, this is not well documented, making it difficult to interpret trends and to evaluate prevention measures. In specific cases, however, it is possible to point to successful improvement of prevention. The Mediterranean fruit fly (medfly) has been the subject of many eradications in the USA (costing over $328 million between 1975 and 1999 (Siebert 1999). Increased effort to prevent introduction and establishment has resulted in an 80% decline in interceptions (USDA APHIS records to 2005) since 1999 and a 75% fall in outbreaks requiring intervention (Vo & Miller 2004) since 1998.

Actual rates of establishment of new pests and diseases are likely to be orders of magnitude lower than introductions (Williamson 1996) and are affected by other factors. The few existing studies have compared establishments per decade over the past century. A study of plant pathogen establishments in the US and invertebrate pests in California shows fluctuating numbers but no upward trend from *ca* 1950 to 1990 (US Congress 1993), while a study of US insect introductions also suggests no pattern of change over a similar period (Sailer 1983). A recent analysis of the rate of new crop disease establishments over the past century in Europe and Africa, based on published reports and records of national and regional quarantine organizations, shows distinctly different patterns in these continents. For Europe, out of 67 recorded establishments of new plant diseases in the twentieth century, 29 (43%) occurred since 1970. For Africa, out of 143 establishments, only 21 (15%) were recorded in those last three decades (Waage *et al.* 2006). Do these differences mean that disease establishments have been increasing in Europe but not in Africa? This might be understood on the basis of Europe's greater international trade, raising concerns about future trade expansion in Africa. However, the same trends may reflect instead an improving plant disease reporting system in Europe and a deteriorating system in Africa. Indeed, reports of African establishments peaked mid-century, during a period of particularly intensive colonial effort in crop introductions and plant pathology. Either way, these observed differences begin to uncover the challenges we face if we are to understand the nature of our agricultural biosecurity threats today.

A statistic on pest and disease establishment is influenced by two processes, the introduction of new species and the 'invasibility' of the affected agroecosystem. Independent of changes in trade and introduction, it is quite probable that modern agriculture has improved the chances of establishment and spread by creating more biologically simplified, uniform and extensive crop and livestock systems. Hence, the impact in the USA in 1970 of a new strain of southern corn leaf blight fungus, *Cochliobolus heterostrophus*, was attributable to the coincidental adoption of a few new, highly susceptible maize varieties that year. These varieties comprised 85% maize production that year, hence losses were enormous, approximately $1bn (Ullstrup 1972; Strange & Scott 2005). In an analysis of factors which facilitate pest and disease invasions in tropical forestry, Nair (2001) found extensive, genetically uniform monoculture to be the key factor. From a biological invasions perspective, theoretical studies on invasion ecology also suggest that more diverse ecosystems will be less invasible (Kennedy *et al.* 2002). However, empirical evidence from invaded, natural communities is more equivocal (Levine & D'Antonio 1999; Levine 2000), possibly because factors which favour diversity like the proliferation of more niches and 'gaps' for colonization also favour invasion by new species.

To summarize, trends in both the trade and the susceptibility of agroecosystems to invasion suggest that rates of establishment of new agricultural pests and diseases should be increasing. While there is some evidence for increasing rates of introduction, evidence of changing rates of establishment is limited. Several complicating factors require that more research is to be done to develop a better evidence base for biosecurity strategy. Biosecurity risks and burdens are growing, by virtue of accumulating new introductions and establishments, but they may not be accelerating.

Before leaving this topic, it is important to stress that the introduction of non-native pests and diseases is only one cause of the emergence of new problems. A recent survey of the drivers of new plant disease emergence worldwide, based on a search of the ProMED database of disease emergence, concludes that the introduction of alien species is associated with 56% of recent outbreaks (Anderson *et al.* 2004). Other drivers of outbreaks include unusual weather events, farming techniques, habitat disturbance, changes in disease vectors and pathogen evolution. A similar study for animal diseases identifies the same kinds of factors underlying disease emergence (Daszak *et al.* 2000).

Host shifts from wild plants and animals to crops and livestock have characterized many cases of pest and disease emergence. They fall outside the scope of this review in that they are often local events, although they may lead to subsequent new introductions elsewhere. The movement of pathogens between wildlife and domestic animals has been a major driver of new disease emergence (Cleaveland *et al.* 2001; Williams *et al.* 2002). For plant pathogens, new disease emergence can be a complex interaction between the introduction of new pathogens, new wild or crop plants and pathogen–host evolution in both (Parker & Gilbert 2004). Local pest and disease evolution interlink with the introduction of new species where introductions add new genotypes which introgress with local strains. Hybridization of pathogens from different origins can create new diseases with new host ranges, as has happened with the alder disease, *Phytophthora alni*, in Europe (Brasier *et al.* 1999). In considering future biosecurity risks, it will be important to evaluate the relative risks from the introduction versus the evolution of new problems and the factors that drive both.

5. ASSESSING THE RISK

Understanding patterns and probabilities of introduction of new pests and diseases is important to assess biosecurity risk, which in turn informs investment in biosecurity measures. Risk analysis has been the standard method underpinning international plant biosecurity for some time, consisting of risk identification, risk assessment and risk management. The IPPC's protocols for pest risk assessment have been widely accepted and stipulate that an organism should be classified as a quarantine pest in terms of likelihood of entry, establishment, spread and economic importance (IPPC 1996). Pest risk assessment is becoming more widely adopted for animal biosecurity as well (Defra 2005*e*).

The formal assessment of biosecurity risk is essentially a 'bio-economic' process (Parker *et al.* 1999; Waage *et al.* 2005*a*,*b*). Biological features of organisms influence their likelihood of introduction, spread and impact. That impact is translated into economic losses and costs to production and trade. In addition, there may be considerable economic 'externalities' associated with a biological invasion. In the 2001 FMD epidemic in the UK, it is estimated that of the losses to the UK economy of approximately £7–8bn, only approximately £355m were attributable to losses to farmers (note: this was still 20% of total farming income over that period). The majority of losses were due to the costs of control and compensation and, particularly, a very large impact on tourism and other aspects of the rural economy (Thompson *et al.* 2002).

In a bio-economic model, it is most easy to capture immediate production and market effects of a breach of agricultural biosecurity. Indirect effects, even if quantifiable, are more difficult to measure and include. Beyond this there are social effects which may be long term, as seen with the FMD epidemic (Donaldson *et al.* 2006) and non-market environmental effects, which we discuss in § 7.

Figure 1 illustrates a bio-economic model which estimates the value of excluding a biosecurity threat to the UK (Waage *et al.* 2005*a*,*b*). This is a stochastic model, based on the @Risk modelling package which is increasingly popular with biosecurity risk assessment. Probability distributions for components of pest introduction, diffusion and growth over a particular interval are postulated, based on empirical studies and modelling of biological invasion (such as Shigesada & Kawasaki 1997) or subjective estimates of these particular parameters. As we have seen, probabilities of introduction are poorly understood, so each is given a distribution which is thought to represent the realistic range of that parameter. A Monte Carlo simulation generates thousands of runs of the model selecting from these probability distributions, which in turn generates an average proportion of the relevant commodity or resource affected over a particular time horizon. From the proportion and level of infestation, an economic value of the infestation is calculated based on the level of loss of overall value and the unit cost of control of the pest or disease. The economic value is discounted over time, reflecting the opportunity cost of investing in alternative productive activities, rather than biosecurity. This model is run over several time horizons, 10, 20 and 30 years, generating a mean and 95% CIs for the value of exclusion. This model assumes a 'do-nothing' approach as a baseline (no prevention, control or eradication), in order to estimate the full benefit of exclusion. The only actions assumed are private measures taken by farmers. Finally, it does not include the indirect and non-market effects to which we have just referred.

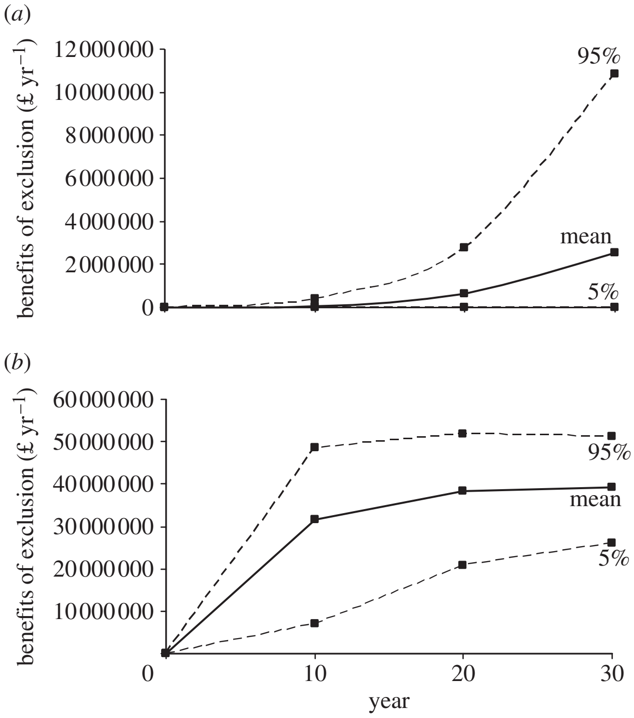

Figure 1. Predicted annual benefits of complete exclusion of (*a*) potato ring rot, *Clavibacter michiganensis* ssp. *sepedonicus* and (*b*) Newcastle disease virus from the UK over 10-, 20- and 30-year time horizons, giving average values and 95% CIs. See text for explanation data from Waage *et al.* (2005) and Cook *et al.* (2006).

Figure 1*a* shows this model run for available information on potato ring rot, *Clavibacter michiganensis* ssp. *sepedonicus*, a bacterial disease which threatens the UK potato industry. A small outbreak of this disease in the UK was eradicated in 2003 (Defra 2005*d*). Figure 1*b* shows the model run for Newcastle disease virus, a highly infectious disease of poultry. The most recent outbreak of this disease on imported pheasants was eradicated in 2005. The benefits of exclusion grow over longer time horizons, as the likelihood of introduction grows with time, as does the spread and impact of any establishment that has occurred, while discounting dampens this effect in the longer term. The most obvious difference between these graphs is in their magnitude; in economic terms, Newcastle disease is a much greater threat, attracting much greater benefits of exclusion. The other distinctive feature is in the shape of the relationships. An appearance of Newcastle disease, if not quickly stamped out, will greatly restrict the export trade in poultry and poultry products, as well as cause direct production losses. This export effect is immediate and causes the benefits of exclusion to rise rapidly over future time horizons. For potato root rot, an export ban would not apply, and the benefits of exclusion rise more linearly over time. These differences in predicted benefits are consistent across a range of biosecurity threats (Waage *et al.* 2005*a*,*b*). Where export bans are imposed on extensively traded commodities, as with many animal diseases, the short-term benefits of taking exclusion measures today are greater than for other kinds of agricultural commodities. Of course, specific predictions of models like these depend on many variables, some of which are very hard

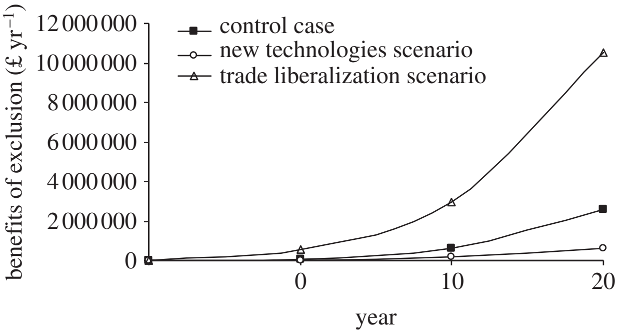

Figure 2. Predicted annual benefits of complete exclusion of a plant disease under two hypothetical scenarios. This is based on the potato ring rot model in figure 1 (control case). In the 'trade liberalization scenario', increased trade raises the probability of disease introduction and reduces the level of local production. In the 'new technology' a new potato variety is developed with substantial resistance to the disease. See text for further explanation. Adapted from Cook *et al.* (2006).

to estimate. A sensitivity analysis can reveal those variables where variation will most affect outcomes, and not surprisingly for both of these disease models, the most sensitive parameter is the probability of entry and establishment of the diseases.

Bio-economic models like these provide a basis for examining and comparing the value of biosecurity investment, for instance, the benefits of prevention versus control (Leung *et al.* 2002; Waage *et al.* 2005*a*,*b*). They can also be used to look at the impact of future changes in drivers of biosecurity risk. For instance, figure 2 takes the potato ring rot model as a general plant disease model and investigates two scenarios (Cook *et al.* 2006). Under 'trade liberalization', there is an increase in the diversity of provenance and volume of potato imports and a substantial jump in the probability of disease introduction, along with a 10% decrease in national potato production, due to this competition from imports. Under 'new technology', a resistant potato variety has been produced which farmers use to greatly reduce the impact of the disease. The economic benefits of investing public funds into exclusion increase under trade liberalization owing to the greater threat posed. While a reduction in national potato production would work against this benefit, it is small relative to the economic value of removing the increased disease risk. Benefits of exclusion decrease with new technology, because this technology makes the disease less costly to 'live with', hence less valuable to exclude.

This quantitative approach to risk, based on the probability of an event and the hazard it presents, underpins much biosecurity thinking today. Getting biosecurity risk estimates wrong has substantial political consequences, the unexpectedly large impacts of the BSE and FMD outbreaks damaged public confidence in government and science (Dibb 2003). It is increasingly clear that one problem with risk assessment is that a quantitative, expert view (objective risk) may be different from that of the public (subjective or perceived risk; Royal Society 1983). Psychometric research shows that perceived risk may be greater than objective risk if it is seen as particularly catastrophic or uncontrollable (dread risk), unobservable and delayed in its action (unknown risks) or as a signal of a much greater problem in society (systematic risks; Slovic 1987). Biosecurity threats share many of these features, particularly for organisms whose impact then extends beyond agriculture, such as zoonotic pathogens. Simberloff (2005) criticizes current risk assessment for biosecurity on the basis of its implicit 'assumption of innocence', the difficulty of imagining all potential effects of an introduction and the problems of quantifying risk parameters, all of which lay risk assessment open to political manipulation and interpretation. The 'precautionary principle' has been widely advocated for biosecurity problems (IUCN 2000) as an alternative to the assumption of innocence and asserts that protective measures, like import restrictions, should not be withheld on the basis of a lack of scientific certainty about risks. This contrasts with the approach taken in the SPS Agreement of the WTO, which requires a scientific basis for proportional response to biosecurity risks. The problem may not be in risk assessment itself, but how we use it to make decisions about an individual biosecurity action, such as exclusion of imports. It may be more effective to focus risk assessment on the goal of an action, rather than on the action itself (O'Brien 2000; Simberloff 2005). For instance, if the risk is to local crop production, developing a resistant variety may be an alternative to restricting imports (figure 2).

However much the risk assessment process may be in need of improvement, risk assessment will be increasingly important because it has been adopted by the World Trade Organization as the basis under which countries may restrict trade for biosecurity reasons. The Sanitary and Phytosanitary (SPS) Agreement of the WTO established a concept of 'appropriate level of protection', the inverse to an acceptable level of risk (http://www.wto.org/english/tratop_e/sps_e/spsagr_e.htm). This is difficult to define or articulate by governments, industries or the public (Mumford 2002). However, national biosecurity authorities should be able to demonstrate that their responses to biosecurity risk are proportional to the scientifically determined threat and that the responses to a range of similar types of risks are consistent, and hence fair to producers, traders, consumers or other stakeholders. The future science of biosecurity risk prediction will need, therefore, to embrace and integrate tools underpinning both objective and perceived risk using quantitative, bio-economic and sociological research methodologies (Mumford 2002).

6. PREVENTION AND ERADICATION

'Prevention is better than cure' is a concept that permeates biosecurity policy (IUCN 2000; Defra 2004). It is subjective insofar as an economic perspective, such as that outlined earlier, would say that this depends on the cost and efficacy of prevention and control systems—a good resistant potato variety may be more cost effective than a potato disease prevention programme. However, it is a bio-economic feature of many invasions that the spread of an invasion is exponential, and both the economic value of losses and the costs of control also increase exponentially, making control very expensive very quickly, and limiting cost-effective eradication to a narrow window of time.

Unwanted pests and diseases may be introduced intentionally or unintentionally. Most agricultural problems arise from accidental introductions, usually contaminants arriving with plant or animal material. By contrast, many pest and disease introductions which now threaten environmental resources, such as invasive plants, fishes and mammals, were intentional introductions whose effect on biodiversity and ecosystem processes had not been anticipated. Prevention strategies will, logically, differ for these different threats. Intentional introductions carry higher risks, because their establishment, or at least continuity, is actively encouraged. Intentional introductions are the subject of very stringent risk assessment in some countries, for instance New Zealand (ERMA NZ 2006). Relative to unintentional introductions, risks of intentional introductions are more easily investigated and predicted prior to introduction, although such prediction is fraught with challenges (Williamson 1996; Smith *et al.* 1999).

We will focus here on unintentional introduction of agricultural pests and diseases, where the principal methodology involves screening and interception of pests on imported materials, informed by international information systems and risk assessment. Currently, inspection systems at ports of entry target commodities and origins suspected of being particularly risky and sample a proportion of imports based on the assessed risks from different sources. Similar commodities from different sources may be inspected at different rates (for example, the EU advises inspection of 5% of citrus from Morocco, 7% from Turkey, 10% from the USA, 15% from Israel, while higher risks warrant inspection of 70% of citrus from Peru (Defra 2006).

The detection of new introductions may occur post entry. Indeed, with increasing container trade, inspection may increasingly shift to points of delivery, rather than arrival ports. Government services regularly survey national agricultural production for new pests and diseases. Contingency plans are developed for the most important animal and plant disease risks. Early detection and action is the priority, and scientific improvement of this capacity is focusing increasingly on new technology which accelerates the detection and confirmation of a new pest and disease introduction. Furthermore, new technology will no doubt be called upon to compensate for limits on manpower for inspections and for losses in taxonomic expertise for diagnosis, both worrying current trends for biosecurity.

A recent foresight project for the UK Office of Science and Technology on 'Detection and identification of infectious diseases' provides an insight into the technological future of agricultural biosecurity (Barker *et al.* 2006). The project reviewed human, animal and plant threats to identify key future risks and their drivers, and then set these against future advances in relevant areas of science to generate a number of specific technological opportunities for detection, identification and monitoring of disease introductions. Three streams of rapidly developing science are converging today to create these opportunities. Advances in nucleic acid research and immunology will make the identification of diseases from samples both fast and inexpensive. Advances in engineering, including miniaturization and nanotechnology, will allow the creation of small, portable biosensors. Advances in information technology and data mining will facilitate the handling of large amounts of epidemiological and other data essential to disease surveillance and prediction. Significantly, these three scientific elements are generic; that is, they will support the development of very similar technology for human, animal and plant biosecurity.

The foresight project identifies four areas of new technology relating to biosecurity.

(i) New technologies for data mining and fusion will lead to global surveillance systems which will pick up unusual patterns of morbidity and mortality and monitor and predict the spread of disease. The use of web-based information systems and disease alert networks to detect and track the recent SARS epidemic showed the potential value of this technology for rapid action against emerging diseases (Kimball *et al.* 2004).

(ii) Tools for characterizing diseases new to science, or variants of existing diseases, will use our growing 'omics' knowledge to predict the biology, host range and pathogenicity of new pathogens before they spread.

(iii) Portable devices for on-the-spot identification of known diseases. This technology is already in prototype for human diseases. Applied to animal and plant systems, it will provide pen- or field-side testing and diagnosis for a range of threats. Microarray technology may permit, ultimately, a national biosecurity chip for diagnosis of all current threats to agriculture.

(iv) Methods for high-throughput screening for disease in humans, animals and plants in areas of concentration, such as ports. Rapid, non-invasive detection of characteristic volatiles or electromagnetic radiation from infected individuals could greatly extend capacity for intercepting new introductions, perhaps in concert with portable on-the-spot detectors once suspect shipments were identified.

Many of these technological advances are underway, stimulated particularly by military research into bioterrorism and biological weapons. The trend towards personalized medicine is creating a market for handheld biosensor devices in medicine. This technology could be extended to provide products for agricultural biosecurity. Some of these opportunities will be taken up by governments where they see a benefit in terms of more cost effective pest and disease detection and suppression. However, for new technology to be most effective, it will require investment and widespread use by the agricultural industry itself. Exporters and importers will use pest and disease detection devices to help them comply with regulation. As that technology becomes more effective, industry interest in its use will increase.

Producers and shippers already bear substantial costs to comply with quarantine regulations. Systematic field pest management, good packing house sanitation and controlled environments during transport and storage reduce the risks of introduction, and can be cited as reasons for reduced inspection, thus providing savings to both public and private sectors. Schemes that provide fast-tracking opportunities to firms with a proven track record in satisfying regulatory requirements, now common in the horticultural export industry, may provide an incentive for meeting standards. Much of this effort is good practice ensuring good market quality, in addition to reducing biosecurity risk, which makes any estimates of private biosecurity compliance costs difficult to separate from meeting market standards.

The apportionment of the costs of prevention in biosecurity is changing, and moving the cost of biosecurity onto export producers, importers and shipping agents is a probable future trend. The Spanish–American medfly incident of 2001 is an example of a shift in the burden of risk management. The USDA intercepted medfly larvae in clementines from Spain in several US states, indicating a potentially widespread quarantine problem. Imports of clementines from Spain to the USA were suspended until satisfactory performance in field, and post-harvest treatments to reduce the risk to an acceptable level could be demonstrated. Spain at the time was exporting 60 000–70 000 tonnes of clementines per year to the USA (CLAM 2003). Following this incident, the industry and government in the major citrus region of Valencia have established an area-wide medfly management programme on over 140 000 ha using sterile insects, traps and aerial bait applications to ensure that the medfly risk from Spanish citrus is negligible (Primo Millo *et al.* 2003). Management costs for the importing government have been reduced, and ultimately the cost is shared by the consumers of imported produce, the exporters and taxpayers in producing regions.

7. AGRICULTURAL BIOSECURITY, A CHANGING LANDSCAPE

Today's agricultural biosecurity systems were built for the protection of national agriculture and food security. Their sectoral roots, in animal and plant protection, have strong historical features that make them different and explain their continuing segregation in most government services. Biosecurity systems have been able to exert substantial control over what comes into a country and to mount high-impact, country-wide eradication programmes. The potential trade conflicts created by different national government biosecurity systems have been substantially mitigated by international agreements which establish common standards and practices. They create a valuable platform for dialogue, and in a few circumstances they have fostered international cooperation in tackling common threats. Agricultural biosecurity remains largely as the business of governments.

Agricultural biosecurity has worked well for substantial threats where large, sustained investment has been made. Examples include the exclusion of several serious animal and plant diseases, and of fruit flies. Overall, however, biosecurity systems are 'leaky', and it is hard to resist the conclusion that in time, entropy will prevail and more pests and diseases will reach more parts of the world. Improving the 'tightness' of the existing system is certainly possible with sufficient government investment. Today, the perceived growth in the biosecurity threat is leading to calls for improvements in these systems. But are these existing systems the ones we want to improve? In this section, we explore three trends which challenge today's biosecurity systems, and in the next we suggest some alternative approaches for the future.

(a) *Trade and consumers*

The traditional status-awarded biosecurity as a vehicle for food security is changing today. Trade liberalization has contributed to this change in two ways. Firstly, it has made it easier and less expensive to import food, reducing concern about food security, and hence domestic food biosecurity. Secondly, it has created a new pro-trade political agenda, associated with the WTO. While the WTO has adopted IPPC and OIE biosecurity practices into its SPS Agreement, it has done so in a way that makes trade barriers a last resort, with the burden of justification falling on the barrier maker (Josling *et al.* 2003). Regional trade and economic agreements, such as those created under the EU and in economic zones in Africa, South America and other regions, will also reduce national control of biosecurity risks.

Trade liberalization will also affect the price differential between domestic and imported products, with important potential implications for government policy on biosecurity. The Organization for Economic Development (OECD) and Consumer Support Estimates (CSE) suggest that, over recent years, EU agricultural prices have been significantly higher than world prices, costing consumers between €50.6 billion and €62.8 billion per annum (OECD 2002). Dominating this calculation are milk products and the beef and veal industries, while the sugar industry also achieves a high percentage CSE due to high EU prices (IEEP 2002). In an economic model, Cook & Fraser (2002) have shown that, where the price of the imported product is less than the locally produced product, consumers' interests will be enhanced by a lower level of biosecurity. This is because biosecurity systems may tend to restrict import of cheaper goods. Add to this the effect of reducing CAP subsidy and support for local industry, and not only might this price differential grow, but local industry may also decrease, making the value to the UK economy of excluding new pests and disease even less (Waage *et al.* 2005*a*,*b*).

For the foreseeable future, the interests of free trade systems and consumers will reduce the regulation of trade as a valuable biosecurity measure.

(b) *Environment and the new biosecurity agenda*

Agricultural biosecurity finds itself today part of a much larger biosecurity agenda. In the 1990s, public and political awareness of the substantial environmental impacts of invasive alien species increased with the inclusion in the Convention on Biological Diversity (CBD) of Article 8h, which required signatory governments to 'prevent, eradicate or control those alien species which affect species, habitats or ecosystems' (CBD 1991). This in turn was based on substantial research over recent decades into 'environmental invasives' including, for instance, predators like cats and rats that exterminated native species, plants which out-competed native flora and covered water bodies, diseases which decimated wildlife and a wide range of alien marine organisms that changed coastal ecosystems (Mooney *et al.* 2005). While the impact of biological invasions on native species and extinction are important (Wilcove *et al.* 1998), perhaps of greater future significance is their broader effect on ecosystem processes, such as water and nutrient cycling, vegetational succession and food chains (Mack & D'Antonio 1998; Mack *et al.* 2000; Orwig 2002). Most environmental invasives are intentional introductions, and many are agricultural in origin, such as forage grasses, forestry trees, new commercial fish and shellfish, or species associated with agricultural introductions, like introduced diseases that move on to native flora or wildlife (Williams *et al.* 2002).

What this means is that agricultural biosecurity is becoming only part of a new national biosecurity agenda. New governmental structures give responsibility for biosecurity to inter-ministerial bodies which link environment, agriculture, trade and other agencies (e.g. the US National Invasive Species Council) or create new biosecurity agencies with this broad coverage, as in Australia and New Zealand. A similar approach has been proposed for the UK (Defra 2003). As this happens, environmental biosecurity priorities may compete with agricultural ones. In the UK today, one of the greatest perceived plant health risks is *P. ramorum*, a fungal disease introduced on horticultural stock which threatens native non-commercial tree species (Defra 2005*c*). Internationally, the IPPC has recently re-interpreted its mandate to include the protection of plants in natural as well as agricultural systems (IPPC 2005).

The societal importance of environmental invasions relative to agricultural ones is difficult to assess—there have been far fewer economic evaluations of environmental invasions (Born *et al.* 2005) and their non-market effects make comparisons difficult (Mumford 2001). But the growing value of local environmental goods to wealthier societies and the fact that, unlike agricultural goods, they are difficult to substitute suggest that their comparative value will not diminish (Waage *et al.* 2005*a*,*b*).

Environmental issues are not the only factors broadening national biosecurity agendas. Concern for human health has dominated recent political discussion of avian influenza, even though it is still only an epidemic disease of poultry, and the high proportion of human diseases of animal origin have focused attention on this zoonotic threat (Cleaveland *et al.* 2001).

Growing environmental and health-related biosecurity agendas will compete with those for agricultural biosecurity, and existing infrastructure for agricultural biosecurity (e.g. inspection services) will be stretched further to cover these new threats.

(c) *Who pays for tomorrow's biosecurity?*

A recent series of economic assessments has had a substantial effect on public and political awareness of biosecurity issues. Studies in the USA estimated the national costs of alien species to be in the tens of billions per year (US Congress 1993; Pimentel *et al.* 2000, 2002), and were a major impetus for a US Executive Order establishing an inter-Departmental National Invasive Species Council in 1996. Now, governments also have substantial, binding contractual commitments, under the CBD, OIE, IPPC and other conventions, to prevent, eradicate or control biosecurity risks. If biosecurity threats are increasing, and we certainly know they are accumulating, the price tag for solving national problems and complying to international agreements is potentially large.

All of these factors have generated considerable interest today in who should pay for biosecurity or, particularly, in moving this burden from the government and tax payer to those responsible for creating the risk. While the government has a broad quarantine remit, investment is often quite focused on particular industries. In 2000, before the FMD outbreak, approximately 90% of operational funding for quarantine activities in the UK was directed at animal disease, and the small allocation to plant disease was directed largely at potato pests. Beyond quarantine, government usually picks up costs of eradication and sometimes compensation as for most losses of livestock due to introduced diseases in the UK. This is not generally true, however, for plant biosecurity; if an importer of nursery stock is shown to be responsible for introducing a pest or disease, they must pay themselves for the cost of destroying infested plants and there is no compensation for their loss. Thus, government investment in biosecurity is actually quite heterogeneous across agriculture.

Private sector participation in biosecurity is particularly likely in the food industry. Where food industries are organized around maintaining thriving export markets, like the Spanish clementine producers described earlier, or have an interest in keeping food chains moving efficiently, like the big multiples that command much of today's food retail market, industry will itself invest in biosecurity as good business. Often, it will do this offshore, by improving the standard of imported produce. However, food is only one pathway of pest and disease introduction, and often a minor one. Further, not all agricultural industries are well organized in this way.

There is a general view that sharing the burden of biosecurity must involve some element of 'polluter pays' and the cost of preventing pests and disease, and of cleaning up outbreaks, should be borne by those who benefit from the process by which they are introduced. This approach, however, has several problems (Mumford 2002). Firstly, while most kinds of industry-related pollution attract one-off 'clean up' costs, biological invasions by their nature grow and become exponentially worse, making the potential cost of a single error so great that the perpetrator cannot possibly pay it. Secondly, biosecurity breaches happen in a context of enormous uncertainty; events are generally so infrequent as to make difficult the identification of who should pay and how much, which makes paying for prevention or even contingency difficult. Finally, the pathways of biological invasion make it difficult to identify those responsible. If a plant disease were to enter the UK from China on a horticultural plant, who is the polluter—the retailer, the importer, the exporter, the producer or all four?

Much research is currently being directed at mechanisms which address this problem (Perrings *et al.* 2000; Mumford 2002; Shogren & Tschirhart 2005). Perrings *et al.* (2005) have reviewed a range of financial mechanisms that include import tariffs, which pay for inspection and the potential cost of clean up, bonds or even tradeable pollution rights. A levy-like system on livestock producers is under consideration by Defra as a means of financing management of future FMD outbreaks in the UK. The common feature of all of these economic models is to extract payments for 'biosecurity risky' activity in order to build up a fund to pay for prevention or control of future biological invasions.

Whatever the mechanism, it would seem inevitable that agricultural biosecurity can no longer be just a game of governments and will need to be played by many more parties.

8. BIOSECURITY: A NEW APPROACH?

Biosecurity systems are increasingly challenged. It is a popular view that an increasing rate of new problems is the cause of this challenge, but we would suggest that changes in the economic and social context of biosecurity may be as, or more significant. New agricultural biosecurity threats, both real *and* perceived, are having enormous economic and societal impacts. This is in part due to a growing awareness of their additional environmental and health effects, as we have seen for avian influenza. At the same time, the economic and social effects of biosecurity measures, including trading blocks and eradication programmes, are today greater and more highly publicized.

At the same time, the traditional role of governments as protectors of biosecurity is increasingly challenged. International trade liberalization and economic 'regionalization' are reducing government powers to erect trade barriers. Underlying this is a potential future conflict between consumers and governments on the balance between cheap imports and biosecurity risk. Resources for agricultural biosecurity will be spread more thinly as more and more diverse biosecurity threats are identified. In such an environment of competition for limited biosecurity resources, specific investment will increasingly depend on strong economic and scientific justification, a holistic approach and risk analysis. Against this backdrop, historical idiosyncrasies that separate systems for animals and plants, or for agricultural and environmental biosecurity issues, may become barriers to progress and sources of public confusion and mistrust.

For these reasons, it may be the time to consider changes in our biosecurity systems which make them more suitable for this new world. Below we suggest three areas drawn from this review, where we might start such a change.

(a) *Integrating biosecurity systems and establishing a common toolkit*

Governments are now dealing with a greater range of biosecurity threats, which extend well beyond traditional agricultural problems and priorities. It is inevitable that they will need to move away from established, sectoral biosecurity traditions focused on a narrow group of stakeholders, and develop a biosecurity system that allows comparison of threats across sectors and draws on a shared toolbox of best practices for measuring risk and evaluating the costs and benefits of prevention, eradication and control.

Besides established tools for risk analysis and cost–benefit analysis, a future toolbox must have means to evaluate:

(i) Indirect effects and externalities, including non-market effects of invasion and its control on the environment and health. This may require a mixture of quantitative and qualitative elements.
(ii) Perception of risk, its elements and how it changes risk measures.
(iii) Uncertainty and its measurement, whether formally through stochastic modelling (as in figure 1) or through adopting a more precautionary approach, or both.

Any assessment is limited by information, and we must do more to collect and analyse useful information on the patterns of movement and introduction of biosecurity threats; we have the tools for this, and increasingly the data, but we are not using these effectively. Advances in modelling will be critical to predicting biosecurity threats and the value of different prevention and control options.

The result of this integrated, scientific approach should be a convergence of plant/animal and agricultural/environmental approaches to biosecurity, with a growing emphasis on proactive and preventative, rather than reactive measures for all. A common technology for detection, identification and monitoring is emerging for animal, plant and other biosecurity threats which will underpin this convergence (Waage *et al.* 2006).

It is not clear the extent to which this harmonization of approach can be achieved with common tools and procedures alone, or whether it requires an integration of different government bodies responsible for biosecurity (for both animal and plant health, or environmental and agricultural protection), as has been the pattern in Australia and New Zealand. Recent developments there, and in the USA with its National Invasive Species Council and Department of Homeland Security, should be treated as experiments and evaluated to examine whether fully integrated systems perform better than traditional ones.

(b) *Greater international cooperation*

Recent trends in biosecurity recommend a shift from a largely national approach to biosecurity towards greater international cooperation. International action against common threats moves biosecurity 'offshore' in a way which can benefit all parties through a shared approach to tackling new threats at their source. There are several specific opportunities for international action.

- (i) Identification of the key pathways for the introduction of new threats and direction of international attention to these: the development and adoption of ballast water exchange conventions in response to marine invasions is an excellent example of a rapid, concerted international response to such a pathway (NRC 1996).
- (ii) Improved international warning networks, like the new global early warning system of OIE, FAO and WHO which will assist in predicting and preventing zoonotic livestock disease problems through monitoring and epidemiological analysis (Ben Jebara 2004).
- (iii) International eradication programmes for animal diseases: we have seen the benefit of global human disease eradication campaigns for smallpox, and the eradication of rinderpest may be imminent. What other animal or plant diseases and pests might be addressed in this manner?
- (iv) Building biosecurity into all aspects of international cooperation: where governments negotiate new activities which involve increased international movement, they should build into their planning the resources to address any increased biosecurity threat. New, cross-border roads, for instance, are notorious boosters of biosecurity threat (Kenmore 2006), as are military campaigns and famine relief programmes (Wittenburg & Cock 2001).

Governments will be careful to weigh up the value to them of investing in national or international biosecurity. However, many are already driven towards the latter by political regionalization. Open trade within a borderless EU now means that a fish disease, for instance, is harder to stop at the UK border, and the UK self-interest shifts to stopping introduction at the outward borders of the EU. Establishment of common economic zones in Africa, Asia, Latin America and elsewhere will compound this effect.

Developing countries may have particularly strong views about international cooperation in biosecurity as a counter to these systems being used as non-tariff trade barriers. Better prevention systems in developed countries, based on risk analysis and new interception technology, disadvantage poorer countries where there is less capacity to measure, document and minimize biosecurity risks. If we accept that, where a country constitutes a ‘weakest biosecurity link’ in a trade network it is advantageous to all parties to improve its biosecurity, we will see investment in capacity building. New technology will come to be seen as ‘trade enabling’ rather than ‘trade blocking’.

(c) *Building a resilient system*

Finally, we must accept that the biosecurity game, however well played, will have the results that more pests and diseases get to more countries. The perceived benefits of free trade may well prove greater than the justification for expending more and more national resources for pest and disease exclusion. Faced with this prospect, we should now begin to put serious consideration into learning to live with this problem, and making our agroecosystems more resilient to biological invasion. It would appear that much recent agricultural development has done the opposite. Opportunities for improving resilience are considerable and include, for example:

- (i) breeding of disease resistance into crops, assisted by new biotechnological tools for incorporating existing or new resistance mechanisms (Persley 2002);
- (ii) development of vaccines for animal diseases which remove the need to exclude and stamp out diseases;
- (iii) strategies of deployment of crops and livestock which reduce the risk of pest and disease outbreaks such as crop varietal mixtures which have proven effective in suppressing plant disease outbreaks (Zhu *et al.* 2000; Mundt 2002); and
- (iv) diversification of local production systems to be ecologically and economically resilient, reducing unnecessary movement of plants and animals.

This last point is particularly relevant to the UK. Intense movement of animals between farms and to distant abattoirs was a contributor to the scale of the 2001 FMD outbreak in the UK, while movement of horticultural material across Europe between planting, growth and sale may be driving the introduction of serious plant diseases into the UK. An analysis of the benefits and costs of indiscriminate movement of plants and animals may reveal strong economic arguments for reducing movement which carries a high public cost relative to a small private benefit.

Along with ecological resilience, there should be an improvement in ‘economic resilience’. Spreading the financial costs of biosecurity more evenly across sectors, and public and private institutions will help to secure this, but it needs engagement of all stakeholders. Novel approaches may help the private sector to cope better with the pressures of biosecurity threats and responses. For example, a fair share of the benefits, and costs, of biosecurity measures should be shared among competing producers, importers and consumers. This may be achieved by broadening the group of stakeholders making decisions about biosecurity issues, to include consumers and overseas partners rather than allowing local producers to dominate decision-making.

A strategic shift from investment in exclusion to that in resilience would be a true challenge for governments playing today’s biosecurity game, particularly given international agreements that could make investors in resilience ‘trade pariahs’. But there are important drivers which might move this forward. In the case of animal biosecurity, for instance, animal welfare considerations may favour investment in vaccination as an alternative to culling strategies. More importantly, a resilience strategy could engage the private sector in picking up more of the cost of biosecurity. Most opportunities to increase resilience, including vaccines, pest and disease resistant crops and protective cropping or farming strategies will take the form of products or processes which producers will pay for themselves. By investing in resilience, governments distribute the burden of paying for biosecurity more evenly between the public and private sector. Some of this cost will inevitably be passed on to consumers, but perhaps this is more fair than sharing those costs across all tax payers in the form of government-funded programmes.

In conclusion, it is unlikely that today's biosecurity systems will change quickly. Many are presently 'locked in' by international agreements, such that change could carry severe trade penalties. But as the cost of running this system becomes greater with more frequent breaches and more expensive trade losses and eradication programmes, there will be mounting pressure to become more proactive and preventative to work together to stop new pests and diseases at their source, and ultimately to achieve freedom from introduced pests and diseases through building in resistance and resilience. New science which advances detection, monitoring and modelling of biosecurity threats and biotechnology for plant and animal resistance will be an important feature of this inevitable evolution of biosecurity systems.

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REFERENCES

Anderson, P. K., Cunningham, A. A., Patel, N. G., Morales, F. J., Epstein, P. R. & Daszak, P. 2004 Emerging infectious diseases of plants: pathogen pollution, climate change and agrotechnological drivers. *Trends Ecol. Evol.* **19**, 535–544. (doi:10.1016/j.tree.2004.07.021)

Anon. 2004 Cow with BSE likely to be one infected animal in the herd. *J. Am. Vet. Med. Assoc.*, 15 February 2004.

Barker, I., Brownlie, J., Peckham, C., Pickett, J., Stewart, W., Waage, J., Wilson, P. & Woolhouse, M. 2006 *Infectious diseases: preparing for the future. A vision of future detection, identification and monitoring systems*. London, UK: Office of Science and Technology.

Baskin, Y. 2002 *A plague of rats and rubbervines: the growing threat of species invasions*. Washington, DC: Island Press.

Ben Jebara, K. 2004 Surveillance, detection and response: managing emerging diseases at national and international levels. *Revue Scientifique et Tecnique, Office International des Epizooties* **23**, 709–715.

Blancou, J. 2003 *Surveillance and control of transmissible animal diseases*. Paris, France: Office International des Épizooties.

Born, W., Rauschmayer, F. & Bräuer, I. 2005 Economic evaluation of biological invasions—a survey. *Ecol. Econ.* **55**, 321–336.

Brasier, C. M., Cooke, D. E. L. & Duncan, J. M. 1999 Origin of a new *Phytophthora* pathogen through interspecific hybridization. *Proc. Natl Acad. Sci. USA* **96**, 5878–5883. (doi:10.1073/pnas.96.10.5878)

Brasier, C. M., Denman, S., Brown, A. & Webber, J. 2004 Sudden oak death (*Phytophthora ramorum*) discovered on trees in Europe. *Mycol. Res.* **108**, 1108–1110. (doi:10.1017/S0953756204221244)

Bright, C. 1998 *Life out of bounds: bioinvasion in a borderless world*. New York, NY: W.W. Norton.

CBD 1991 "Convention Text", *Convention on biological diversity*. See http://www.biodiv.org/convention/articles.asp.

CLAM 2003 *Mediterranean citrus industry statistics*. Madrid, Spain: CLAM.

Clarke, M. 2004 Phytosanitary measures: preventing the introduction of exotic pests and pathogens occurring from the global trade of wood products. Working papers of the Finnish Forest Research Institute 1. See http://www.metla.fi/julkaisut/workingpapers/2004/mwp001-09.pdf.

Cleaveland, S., Laurenson, M. K. & Taylor, L. H. 2001 Diseases of humans and their domestic mammals: pathogen characteristics, host range and the risk of emergency. *Phil. Trans. R. Soc. B* **356**, 991–999. (doi:10.1098/rstb.2001.0889)

Cock, M. J. W. 2003 Biosecurity and forests: an introduction—with particular emphasis on forest pests. FAO forest health and biosecurity working paper FBS/2E, 2003. See ftp://ftp.fao.org/docrep/fao/006/j1467e/J1467E.pdf.

Cook, D. C. & Fraser, R. W. 2002 Exploring the regional implications of interstate quarantine policies in western Australia. *Food Policy* **27**, 143–157. (doi:10.1016/S0306-9192(02)00008-8)

Cook, D. C., Waage, J. K., Mumford, J. D., Fraser, R. W. & Wilby, A. 2006 The benefits of potato ring rot exclusion from the United Kingdom. Department of Trade and Industry Foresight project on the Detection and Identification of Infectious Diseases.

CIMMYT 2005 *Sounding the alarm on global stem rust: an assessment of race Ug99 in Kenya and Ethiopia and the potential for impact in neighboring regions and beyond*. Expert Panel on the Stem Rust Outbreak in Eastern Africa. Mexico City: International Maize and Wheat Improvement Center (CIMMYT) (September 8). See http://www.cimmyt.org/english/wps/news/2005/aug/pdf/Expert_Panel_Report.pdf.

Daszak, P., Cunningham, A. A. & Hyatt, D. D. 2000 Emerging infectious diseases of wildlife—threats to biodiversity and human health. *Science* **287**, 443–449. (doi:10.1126/science.287.5452.443)

Defra 2002 Bluetongue disease control strategy for the United Kingdom. London, UK: DEFRA. See http://www.defra.gov.uk/animalh/diseases/notifiable/disease/bluetongue_control_strategy.pdf.

Defra 2003 Review of non-native species policy: report of the working group. PB8072. London, UK: Defra Publications.

Defra 2004 *Animal health and welfare strategy for Great Britain*. London, UK: Defra Publications.

Defra 2005*a* Biosecurity guidance to prevent the spread of animal diseases. See http://www.defra.gov.uk/animalh/diseases/pdf/biosecurity_guidance.pdf.

Defra 2005*b* Plant health strategy for England. PB11158. London, UK: Defra Publications.

Defra 2005*c* *Phytophthora ramorum*. Plant health. Information sheet. See http://www.defra.gov.uk/planth/pramorum.htm.

Defra 2005*d* Revised final report into the 2003 potato ring rot outbreak in the UK. London, UK: Defra Publications. See http://www.defra.gov.uk/planth/ring/2005/revring.pdf.

Defra 2005*e* Qualitative risk analysis: animal disease outbreaks in countries outside the UK. Defra Animal Health and Welfare. See http://www.defra.gov.uk/animalh/diseases/monitoring/riskassess.htm.

Defra 2006 Second working group on reduced frequency of checks. News release from Plant Health Division, Defra. See http://www.defra.gov.uk/planth/newsitems/reddec05.htm.

Dibb, S. 2003 Winning the risk game. London, UK: National Consumer Council. See http://www.ncc.org.uk/risk/risk_game.pdf.

Donaldson, A., Lee, R., Ward, N., Wilkinson, K. 2006. Foot and mouth—five years on: the legacy of the 2001. Foot and mouth disease crisis for farming and the British Countryside. Centre for rural economy discussion paper series no. 6. Newcastle, UK: Newcastle University.

ERMA New Zealand 2006 Preventing or managing risk to people and the environment. See http://www.ermanz.govt.nz.

Everett, R. A. 2000 Patterns and pathways of biological invasions. *Trends Ecol. Evol.* **15**, 177–178. (doi:10.1016/S0169-5347(00)01835-8)

FAO 2003 Biosecurity in food and agriculture. Report on the 17th Session of the committee on agriculture, Rome 31 March–4 April 2003. See http://www.fao.org/DOCREP/MEETING/006/Y8453E.HTM.

Goodwin, S. B., Cohen, B. A., Deahl, K. L. & Fry, W. 1994 Migration from Northern Mexico as the probable cause of recent genetic changes in populations of *Phytophthora infestans* in the United States and Canada. *Phytopathology* **84**, 553–558. (doi:10.1094/Phyto-84-553)

Harder, T. C. & Werner, O. 2006 Avian influenza. In *Influenza report* (eds B. S. Kamps, C. Hoffmann & W. Preiser). Flying Publisher. See http://www.influenzareport.com/ir/ai.htm

Hedrick, R. P. 1996 Movement of pathogens with the international trade of live fish: problems and solutions. *Revue Scientifique et Technique*. **15**, 523–531.

Hill, B. J. 2000 International trade in farmed fish and shellfish: the impact of disease spread. In *Safeguarding animal health in global trade* (moderators: Thierman, A., Moenig, M.). Online Conf. on Sustainable Agricultural Production. Braunschweig, Germany: Federal Agricultural Research Centre, FAL. See http://agriculture.de/acms1/conf6/ws9fish.htm.

IEEP 2002 *The common agricultural policy: how the CAP operates, the key commodities, competitors and markets for the European Union*. Brussels, Belgium: Institute for European Environmental Policy.

Independent 2003 Gardeners sound alarm over unprecedented invasion by foreign pests.

IPPC 1996 ISPM2 Guidelines for pest risk analysis. Rome, Italy: IPPC/FAO.

IPPC 2005 Identification of risks and management of invasive alien species using the IPPC framework. In *Proc. Workshop in Braunschweig, Germany 22–26 September 2003*. Rome, Italy: International Plant Protection Convention Secretariat, FAO.

IUCN 2000 Guidelines for the prevention of biodiversity loss caused by alien invasive species, Prepared by the Invasive Species Specialist Group, Species Survival Commission, International Union for the Conservation of Nature. Gland, Switzerland. See http://www.iucn.org/themes/ssc/pubs/policy/invasivesEng.htm.

Josling, T., Roberts, D. & Orden, D. 2003 *Food regulation and trade. Towards a safe and open global system*. Washington, DC: Institute for International Economics.

Kenmore, P. E. 2006 New roads, new diseases. In *Infectious diseases: preparing for the future. A vision of future detection, identification and monitoring systems* (eds I. Barker, J. Brownlie, C. Peckham, J. Pickett, W. Stewart, J. Waage, P. Wilson & M. Woolhouse). London, UK: Office of Science and Technology.

Kennedy, T. A., Naeem, S., Howe, K. M., Knops, J. M. H., Tilman, D. & Reich, P. 2002 Biodiversity as a barrier to ecological invasion. *Nature* **417**, 636–638. (doi:10.1038/nature00776)

Kimball, A. M., Lober, B., Kobayashi, A., Arima, Y., Fox, L., Brown, J. & Pautler, N. F. 2004 Reporting, surveillance, and information exchange: the SARS imperative for innovation. In *Learning from SARS: preparing for the next disease outbreak* (eds S. Knobler, A. Mahmoud, S. Lemon, A. Mack, L. Sivitz & K. Oberholtzer), pp. 222–230. Washington, DC: National Academies Press.

Leung, B., Lodge, D. M., Finnoff, D., Shogren, J. F., Lewis, M. A. & Lamberti, G. 2002 An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. *Proc. R. Soc. B* **269**, 2407–2413. (doi:10.1098/rspb.2002.2173)

Levine, J. M. 2000 Species diversity and biological invasions: relating local process to community pattern. *Science* **288**, 852–854. (doi:10.1126/science.288.5467.852)

Levine, J. M. & D'Antonio, C. M. 1999 Elton revisited: a review of evidence linking diversity and invasibility. *Oikos* **87**, 15–26. (doi:10.2307/3546992)

Lindquist, D. A., Abusowa, M. & Hall, M. J. 1992 The New World screwworm fly in Libya: a review of its introduction and eradication. *Med. Vet. Entomol.* **6**, 2–8.

Mack, R. N., Simberloff, D., Lonsdale, W. M., Evans, H., Clout, M. & Bazzaz, F. A. 2000 Biotic invasions: causes epidemiology, global consequences and control. *Ecol. Appl.* **10**, 689–710.

Mack, M. C. & D'Antonio, C. M. 1998 Impacts of biological invasions on disturbance regimes. *Trends Ecol. Evol.* **13**, 195–198. (doi:10.1016/S0169-5347(97)01286-X)

Mooney, H. A., Mack, R. N., McNeely, J. A., Neville, L. E., Schei, P. J. & Waage, J. K. 2005 *Invasive alien species: a new synthesis*. Washington, DC: Island Press.

Mumford, J. D. 2001 Environmental risk evaluation in quarantine decision making. In *The economics of quarantine and the SPS agreement* (eds K. Anderson, C. McRae & D. Wilson), pp. 353–383. Adelaide/Canberra, Australia: Centre for International Economic Studies/AFFA Biosecurity.

Mumford, J. D. 2002 Economic issues related to quarantine in international trade. *Eur. Rev. Agric. Econ.* **29**, 329–348. See http://erae.oupjournals.org/cgi/reprint/29/3/329.pdf.

Mundt, C. C. 2002 Use of multiline cultivars and cultivar mixtures for disease management. *Annu. Rev. Phytopathol.* **40**, 381–410. (doi:10.1146/annurev.phyto.40.011402.113723)

Nair, K. S. S. 2001 *Pest outbreaks in tropical forest plantations: is there a greater risk for exotic tree species?* Bogor, Indonesia: Center for International Forestry Research.

National Audit Office 2003 *Protecting England and Wales from plant pests and diseases*. London, UK: The Stationary Office.

National Research Council 1996 *Stemming the tide: controlling introductions of nonindigenous species by ships ballast water*. Washington, DC: National Academy Press.

National Research Council 2002 *Predicting invasions of nonindigenous plants and plant pests*. Washington, DC: National Academy Press.

Nugent, R., Benwell, G., Geering, W. K., McLellan, J., Mumford, J. D., Quinlan, M. & Zelasny, B. 2001 Economic impacts of transboundary plant pests and animal diseases. In *The state of food and agriculture 2001. Part III*. Rome, Italy: FAO Information Division.

O'Brien, M. 2000 *Making better environmental decisions: an alternative to risk assessment*. Boston, MA: MIT Press.

OECD 2002 Agricultural policies in OECD countries: monitoring and evaluation 2002. Paris, France: Organisation for Economic Cooperation and Development.

OIE 2005 World animal health information system. Paris, France: OIE. See http://www.oie.int/eng/info/en_info.htm.

Orwig, D. A. 2002 Ecosystem to regional impacts of introduced pests and pathogens: historical context, questions and issues. *J. Biogeogr.* **29**, 1471–1474. (doi:10.1046/j.1365-2699.2002.00787.x)

O'Toole, T. & Inglesby, T. V. 2003 Toward biosecurity. *Biosec. Bioterror. Biodef. Strat. Prac. Sci.* **1**, 1–3. (doi:10.1089/153871303605147 60)

Parker, I. M. & Gilbert, G. S. 2004 The evolutionary ecology of novel plant–pathogen interactions. *Annu. Rev. Ecol. Evol. Syst.* **35**, 675–700. (doi:10.1146/annurev.ecolsys.34.011802.132339)

Parker, I. M. *et al.* 1999 Impact: towards a framework for understanding the ecological effects of invaders. *Biol. Inv.* **1**, 3–19. (doi:10.1023/A:1010034312781)

Peeler, E., Thrush, M. & Gardiner, R. 2003 A preliminary risk analysis for the transmission of the exotic fish parasite *Gyrodactylus salaris* between river catchments in England and Wales. Dorset, UK: The Centre for Environment, Fisheries and Aquaculture Science.

Pegram, R., Indar, L., Eddi, C. & George, J. 2004 The Caribbean *Amblyomma* program: some ecologic factors affecting its success. *Ann. NY Acad. Sci.* **1026**, 302–311. (doi:10.1196/annals.1307.056)

Perrings, C., Williamson, M. & Dalmazzone, S. (eds) 2000 *The economics of biological invasions*. Northampton, MA: Edward Elgar Publishing.

Perrings, C., Dehnen-Schmutz, K., Touza, J. & Williamson, M. 2005 How to manage biological invasions under globalization. *Trends Ecol. Evol.* **20**, 212–215. (doi:10.1016/j.tree.2005.02.011)

Persley, G. J. 2002 Agricultural biotechnology: global challenges and emerging science. In *Agricultural biotechnology: country case studies* (eds G. J. Persley & L. R. MacIntyre), pp. 1–37. Wallingford, UK: CAB International.

Pimentel, D., Lach, L., Zuniga, R. & Morrison, D. 2000 Environmental and economic costs associated with non-indigenous species in the United States. *BioScience* **50**, 53–65. (doi:10.1641/0006-3568(2000)050[0053:EAECON]2.3.CO;2)

Pimentel, D. *et al.* 2002 Economic and environmental threats of alien plant, animal and microbe invasions. In *Biological invasions: economic and environmental costs of alien plant, animal and microbe species* (ed. D. Pimentel), pp. 307–329. London, UK: CRC Press.

Primo Millo, E., Alfaro Lassala, F. & Argiles Herrero, R. 2003 Plan de actuacion contra la mosca de las frutas (*Ceratitis capitata*) en la Comuidad Valencian. *Phytoma Espana* **153**, 127–130.

Royal Society 1983 *Risk assessment: a study group report*. London, UK: Royal Society.

Sailer, R. I. 1983 History of insect introductions. In *Exotic plant pests and North American agriculture* (eds C. L. Wilson & C. L. Graham), pp. 15–38. New York, NY: Academic Press.

Shigesada, N. & Kawasaki, K. 1997 *Biological invasions: theory and practice*. Oxford, UK: Oxford University Press.

Shogren, J. F. & Tschirhart, J. 2005 Integrated ecology and economics to address bioinvasions. *Ecol. Econ.* **52**, 267–271.

Siebert, J. 1999 Update on the economic impact of Mediterranean fruit fly on California agriculture. *Subtrop. Fruit News* **7**, 16–18.

Simberloff, D. 2005 The politics of assessing risk for biological invasions: the USA as a case study. *Trends Ecol. Evol.* **20**, 216–222. (doi:10.1016/j.tree.2005.02.008)

Slovic, P. 1987 Perception of risk. *Science* **236**, 280–285. (doi:10.1126/science.3563507)

Smith, C. S., Lonsdale, W. M. & Fortune, J. 1999 When to ignore advice: invasion predictions and decision theory. *Biol. Inv.* **1**, 89–96. (doi:10.1023/A:1010091918466)

Strange, N. & Scott, P. R. 2005 Plant disease: a threat to global food security. *Annu. Rev. Phytopathol.* **43**, 83–116. (doi:10.1146/annurev.phyto.43.113004.133839)

Thompson, D., Muriel, P., Russell, D., Osborne, P., Bromley, A., Rowland, M., Creigh-Tyte, S. & Brown, C. 2002 Economic costs of the foot and mouth disease outbreak in the United Kingdom in 2001. *Revue Scientifique et Tecnique, Office International des Epizooties* **21**, 675–687.

Ullstrup, A. J. 1972 The impacts of the southern corn leaf blight epidemics of 1970–1971. *Annu. Rev. Phytopathol.* **10**, 37–50. See http://arjournals.annualreviews.org/doi/abs/10.1146/annurev.py.10.090172.000345.

US Congress, Office of Technology Assessment 1993 Harmful non-indigenous species in the United States. OTA-F-565. Washington, DC: US Government Printing Office.

USDA 2004 Karnal Bunt: a fungal disease of wheat. USDA APHIS plant protection and quarantine factsheet March 2004. See http://www.aphis.usda.gov/lpa/pubs/fsheet_faq_notice/fs_phkarnal.html.

USDA 2005 Animal and plant health inspection service. Strategic plan 2003–2008 Updated March 2005. United States Department of Agriculture Marketing and Regulatory Programs. See http://www.aphis.usda.gov/about_aphis/downloads/APHIS_SPlan3-05.pdf.

Vo, T. & Miller, C. E. 2004 Economic evaluation of APHIS fruit fly programs. USDA-APHIS Policy and Program Development, 23 pp. Riverdale, MD: USDA.

Waage, J. K., Fraser, R. W., Mumford, J. D., Cook, D. C. & Wilby, A. 2005*a* *A new agenda for biosecurity*. Horizon Scanning Programme, Department for Environment, Food and Rural Affairs, UK.

Waage, J. K., Mumford, J. D., Fraser, R. W., Wilby, A. & Cook, D. C. 2005*b* Non-native pest species: changing patterns mean changing policy issues. In *Crop Science and Technology 2005*. *Proc. BCPC Int. Cong*, pp. 725–732.

Waage, J. K., Spence, N., Woodhall, J., Bishop, S., Smith, J. J. 2006 Patterns of new plant disease and pest emergence—evidence of a growing problem? In (I. Barker, J. Brownlie, C. Peckham, J. Pickett, W. Stewart, J. Waage, P. Wilson & M. Woolhouse 2006) Infectious diseases: preparing for the future. A vision of future detection, identification and monitoring systems. London, UK: Office of Science and Technology.

Whiting, T. L. 2003 Foreign animal disease outbreaks, the animal welfare implications for Canada: risks apparent from international experience. Special report. *Can. Vet. J.* **44**, 805–815.

Wilcove, D. S., Rothstein, D., Dubow, J., Phillips, A. & Losos, E. 1998 Quantifying threats to imperilled species in the United States. *Bioscience* **48**, 607–615. (doi:10.2307/1313420)

Williams, E. S., Yuill, T., Artois, M., Fischer, J. & Haigh, S. A. 2002 Emerging infectious diseases in wildlife. *Revue Scientifique et Tecnique, Office International des Epizooties* **21**, 139–157.

Williamson, M. 1996 *Biological invasions*. London, UK: Chapman and Hall.

Wittenberg, R. & Cock, M. J. W. 2001 *Invasive alien species: a toolkit of best prevention and management practices*. Wallingford, UK: CAB International.

Woolhouse, M. E. J., Haydon, D. T. & Antia, R. 2005 Emerging pathogens: the epidemiology and evolution of species jumps. *Trends Ecol. Evol.* **20**, 238–244. (doi:10.1016/j.tree.2005.02.009)

Work, T. T., McCullough, D. G., Cavey, J. F. & Komsa, R. 2005 Arrival rate of nonindigenous insect species into the United States through foreign trade. *Biol. Inv.* **7**, 323–332. (doi:10.1007/s10530-004-1663-x)

Zhu, Y. *et al.* 2000 Genetic diversity and disease control in rice. *Nature* **406**, 718–722. (doi:10.1038/35021046)