T15: Patterns of new plant disease spread: a plant pathogen database analysis

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Introduction

There is a general concern that globalisation is accelerating the spread of plant and animal disease. Increases in both the international movement of agricultural goods due to trade liberalisation (Josling 2003) and in the international movement of people and materials (Meagher 2006) have been associated with a growing threat of disease introduction. New awareness of so-called 'bio-invasions' has stimulated international interest, with a number of countries modifying existing quarantine arrangements into more comprehensive 'biosecurity' systems so as to better address this threat (Waage and Mumford in press).

In the UK, a recent series of highly publicised disease introductions, including foot and mouth disease, Newcastle disease, avian influenza, potato ring rot and sudden oak death, has heightened awareness, and led to similar recommendations (Defra 2003).

However, the evidence that a growth in international trade and traffic has driven the introduction and establishment of new diseases is largely anecdotal. A perceived increase in disease introductions in recent years is not sufficient proof of a trend.. There is a need to establish an evidence base for growing disease threat through the careful, statistical study of trends over long time periods. In so doing, we will better understand the precise nature of new disease introductions and the causal relationship, if any, between globalisation and disease threat.

The Foresight Project on Detection and Identification of Infectious Diseases (Barker *et al*. 2006) has examined the future global threat of plant, animal and human disease and identified growing trade and traffic as a major driver. This study explores the evidence for this prediction by examining historical trends in new plant disease introduction and establishment. We select plant diseases for two reasons. Firstly, the emergence of new plant disease constitutes a future threat to human wellbeing and, particularly, to the achievement of millennium development goals, by creating food insecurity and economic disruption. While the chronic plant disease burden on production is substantial, particularly in developing countries, of particular concern are specific, local epidemics. These sudden outbreaks can have short-term, devastating effects on economies. The Irish Potato Famine of the 1840s is a haunting reminder of this (Hardwick 2006), while recent epidemics of cassava mosaic disease, banana bacterial wilt and coffee wilt in Africa illustrate graphically the continuing capacity of plant epidemics to affect food security and economic stability, particularly in the developing world (Quinlan et al. 2006). In recent years, as throughout history, plant disease epidemics often result from the introduction of new diseases from other regions.

Secondly, plant diseases are remarkably diverse. Most plants host a range of relatively specific species or strains of fungi, bacteria, viruses and phytoplasms. Thus, with as many as 150 species of cultivated plants, the pool of potential introduced crop diseases is enormous. Because of this, it is possible to compile reasonably large datasets of new disease establishments over time, where each datum represents a new introduction of a unique species or strain. This is not possible for animal and human disease systems where there are only a handful of diseases for study and where the ‘first establishment’ of any of these to a country or region mostly occurred in the distant past.

Further, the history of animal and human disease eradication and control makes it difficult to interpret a pattern of successive national or regional outbreaks of a single disease as a series of ‘new, discrete establishments’. They may simply indicate re-emergence of an already established infection. Hence, plant diseases offer the greatest promise in building and examining an evidence base for changing patterns of disease movement and establishment.

This Foresight project has a specific objective of comparing future disease threats in the UK and sub-Saharan Africa, in part because globalisation will make any threat a global threat, and in part because of a focus on achieving millennium development goals. In this study, we also make this comparison. However, in order to generate datasets of suitable and roughly comparable size, we compare new plant disease establishments in Europe and Africa, two continents with very different agricultural and trading histories.

Hypothesis and current evidence

In this study, we examine the hypothesis that the reported establishment of new, introduced plant diseases has been accelerating over time, by analysing trends in new plant disease introductions over the past century. In framing this hypothesis, we have been careful to account for the following points:

1. Newly introduced diseases, once established, rarely disappear. Hence they tend to accumulate over time. Even a constant or declining rate of introduction will lead to an accumulation of disease and a perceived growing disease burden. Our hypothesis examines trends relating to globalisation and the growth in international trade and traffic, and therefore postulates a growing rate of new disease establishment.

2. The great majority of new pathogens which enter a country will not establish themselves as locally reproducing, spreading disease problems. Hence, there is a potential difference between patterns of introduction of new diseases and patterns of establishment. We report only records of establishment, because these identify those introductions that will actually affect economies. Indeed, their reporting as new crop diseases supports our assumption that they are potentially important.

3. The reporting of new diseases is profoundly affected by effort. While important new diseases are unlikely to escape attention for long, the detection of some diseases may be delayed or even missed altogether if national surveillance and diagnostic capacity is poor. So, we can only analyse reported rates of introductions, not true rates,

and we evaluate the implications of this in the Discussion section below.

4. Introduction of non-native pathogens is not the only mechanism underlying the emergence of new plant diseases. There is considerable evidence that pathogens can adapt or evolve locally so as to create new disease in native or introduced crops. We focus here on new introductions, as they relate specifically to globalisation, and we return to the broader issue of new disease emergence in the Discussion.

There have been very few comparative studies of patterns of new agricultural disease or pest introductions, despite their national and regional importance. Generally there are simply reports of new interceptions and establishments. Interceptions are increasingly recorded and analysed by quarantine authorities, while establishments are recorded in scientific journals or by national or international organisations because of their trade implications, but these accounts are often scattered and rarely accumulated and analysed.

Recent interest in biosecurity has led to more formal collection and analysis of interception data at ports. Thus, patterns of interceptions of non-native arthropod species at US ports from 1990 to 1999 suggest an increasing trend (National Research Council 2002). New pest and disease outbreaks recorded by Defra in the UK fluctuate around 150 from 1993 to 2000 and then jump to 350 in 2002 (National Audit Office 2003). Note that these interception and outbreak records include repeated appearance of non-native pests and diseases, hence these trends may indicate an increasing volume of new problems, not necessarily an increasing diversity. As mentioned above, reporting is likely to be proportional to effort (Clarke 2004, Work et al. 2005): a recent increase in effort could also yield a positive trend in interceptions.

Only a very few studies have compared establishment of new pests and diseases over time. A study of plant pathogen establishments in the US and invertebrate pests in California show fluctuating numbers but no upward trend from about 1950 to 1990 (US Congress 1993), while a study of US insect pest introductions also suggests no pattern of change over a similar period (Sailer 1983). An analysis of European records selected from a regional quarantine database suggests increasing establishment of new plant diseases and insect pests over the past century (Waage et al. 2005). The balance of evidence to date suggests a possible recent increase in interception of new plant diseases, but patterns of establishment, such as they are, are equivocal.

Materials and Methods

In this study, we evaluate for the first time an historical dataset on new crop disease establishments. This dataset has been compiled from reports of new pest and disease occurrences in European and African countries over the 20th Century, published in the scientific literature. Principal sources of information include: the disease distribution maps and electronic compendia compiled by CAB International (CABI 1998,2006), the Inter-Africa Phyto-Sanitary Council of the Organization of African Unity (IAPSC 1985) and the European Plant Protection Organisation (EPPO 2005). We also used regularly updated databases, including CABI Distribution Maps of Plant Diseases, the EPPO Reporting Service, Disease Notes of the American Phytopathological Society, New Disease Reports of the British Society for Plant Pathology and the ProMed database. We are also grateful to a number of European and African plant disease specialists and taxonomists for information and comments.

The use of this data to interpret rates of new disease establishment over time is not straightforward. The accuracy and completeness of these records is variable. Old records may refer to species which have since been renamed or split, making it difficult to establish the identity of the introduced species, or there may simply be mis-identifications. Often, some important piece of information is missing from a record, such as the date of first reporting in a continent, thereby excluding that entire species from analysis despite its national or regional significance. Finally, there is the problem of defining an 'establishment'. While most reports of new pests and diseases relate to a permanent establishment, there may be some instances where this establishment is short lived, or where subsequent establishments in other countries in the region are more significant. However, in order to be consistent, we had no alternative but to use the first report in the first country.

For all these potential shortcomings, many of which are already addressed by compilers of the quarantine compendia which we used, we believe, however, that this is the best information available for analysis on reported new diseases.

Records were collected from the literature of the first appearance of a crop disease in a country within the continent. For Europe, we included all European countries to the border of the former USSR and Turkey, excluding the Canary Islands and dependent territories. For Africa, we included all countries on the continent, including Madagascar and Mauritius. A specific disease could be a pathogen species or a host-specific variant of a species widely recognised as a distinct pathogen. We included records of fungi (including Straminipila), bacteria and viruses but not phytoplasms or nematodes. Insect pests are the subject of a separate analysis.

Note that we included only one continental establishment per disease. This means that all subsequent introductions of a disease into the continent, be they re-introductions to different parts of the continent or spread of the disease around the continent, are not included. This drastically limits introduction records, but to do otherwise would, we believe, have introduced a kind of 'pseudo-replication' which would have greatly biased the data. Hence, many significant and spectacular, first national introductions are not included, only the first continental one.

There is much to be gained from the study of the spread of diseases between nations after first introduction, particularly in terms of rate of spread and pathways, but that is another project.

While the principal objective of the study was to examine rates of establishment, data was collected where possible on a number of other aspects of each introduction. For each record of pest introduction, an effort was made to collect the following:

1. Latin and common names of disease
2. Plant species affected
3. Country of first report in the continent
4. Presumed country or region of origin
5. Year of first report
6. Likely pathway of introduction, as reported in the literature

The pattern of establishments over time was generated by clustering records according to the decade of introduction. Thus, an introduction in the 1920s means a reported introduction between 1921 and 1930, and so on. Where no date was known, the report was not used, whereas for a report such as ‘by 1950’ or ‘before 1950’, an introduction in the 1940s was recorded. While this may bias introductions towards more recent dates, it is consistent in recording first reportings. Indeed, specific records of establishment, e.g. 1957, may still only record first discovery, not first establishment. We exclude from analysis records before 1901 and after 2000, but comment on these in the Discussion.

The crops affected were put into classes for comparison: field crops (including food and industrial crops such as vegetables, pulses, potatoes, cotton); cereals (as a separate category of field crops); perennial tree and bush crops (for fruit/nuts, including industrial tree crops like coffee and cocoa); forestry crops and other tree species (including timber crops but also amenity trees); and horticultural crops (specifically ornamentals).

For analysis of the geographical origin of pathogens and insects, regions of origin were clustered according to six continental areas: North America, South America, Europe, Africa, Asia and Australasia. For a disease of fruit trees originating in east Asia, there may be a specific report that its introduction into Europe or Africa was with planting materials from the USA. However, more often than not, no such record of immediate origin exists. Hence, when recording the origin of diseases, we used all available reports of specific pathways of introduction, but otherwise cited the likely region of origin of the disease itself.

Specific pathways for first introduction of diseases and pests were occasionally reported in the literature, e.g. ‘from North America on shipments of apple planting material’. More often, however, they were not. In the latter case, we used known pathways for that species or proposed pathways based on biology, e.g. potato diseases on tubers, wheat diseases on seeds, unless those diseases were not tuber- or seed-borne.

Throughout this analysis, where a field had no information, that record was excluded from the analysis using that field. Overall, 186 substantially complete reports of disease establishments were obtained for Africa, and 91 reports for Europe. The data are available for analysis in Excel format.

Results

The pattern of new disease reports, clustered by decade, is shown in Figure 1. For Europe, there is an indication that the rate of new disease reporting has increased gradually over the 20th century, with a substantial increase in the last decade. For Africa, there is a very different trend. A dramatic increase in reports occurred early in the century, but this has tailed off towards 2000. A substantial number of African introductions were into countries bordering the Mediterranean. On inspection of the data, we conclude that it is quite likely that many of these introductions may reflect the spread of diseases introduced into Europe. Therefore, we examine the effect of their exclusion on African trends (Figure 1), and find little change in the overall pattern. In the following analyses, where we exclude countries bordering the Mediterranean from African disease reports, we refer to this as ‘sub-Saharan Africa’, but note that we are using this term in a very restrictive sense.

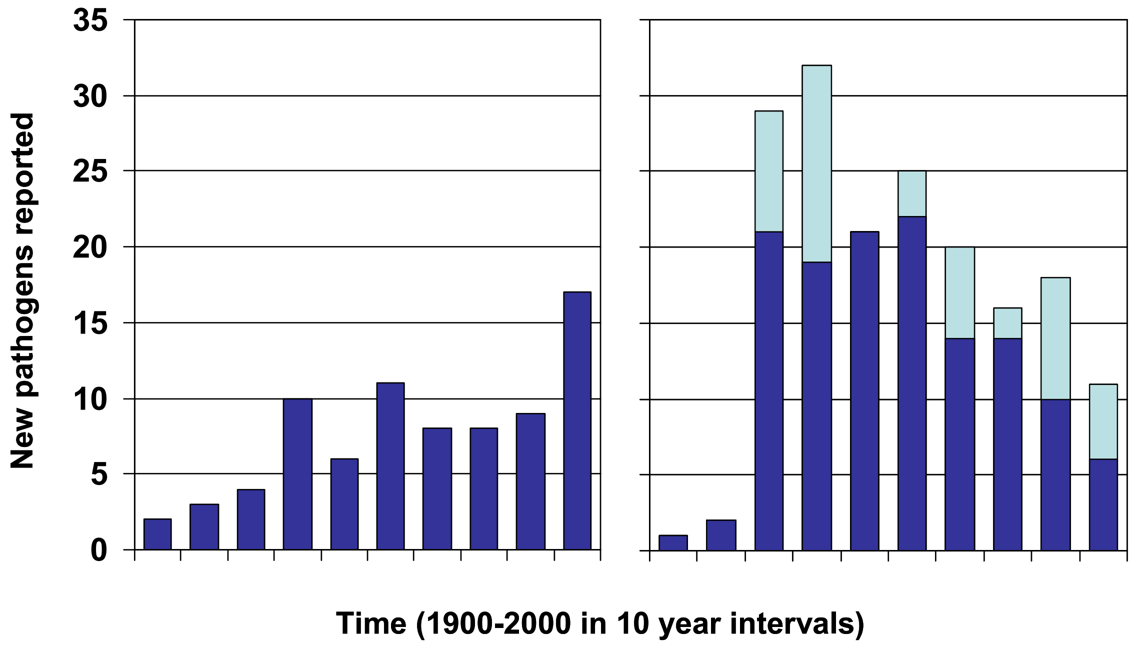

Figure 1. *Number of new crop pathogen species reported per decade over the 20th Century in Europe (left) and Africa (right). For Africa, pale blue indicates species report in countries bordering Mediterranean (Egypt, Libya, Tunisia, Algeria, Morocco).*

In the Discussion, we consider whether these European and African patterns, and their striking differences, reflect the true history of disease introduction and establishment, or historical patterns of effort in reporting new diseases, or both.

Figure 2 shows the pattern of new disease reports over time on different plant types, for each region. The top graphs show field crops, and reveal a substantially greater level of introduction of diseases into cereals in Africa. Overall, 12% of reported new field crop diseases in Africa have been on cereals, compared to 4% in Europe. If we consider staple, starch-based food crops which make up most of our global food supply, including cereals, root crops like potatoes and cassava, and bananas in Africa (included for our analysis as 'perennial tree crop'), then 18% of disease introductions into Africa have been on staple cereal and root crops, compared to 11% in Europe.

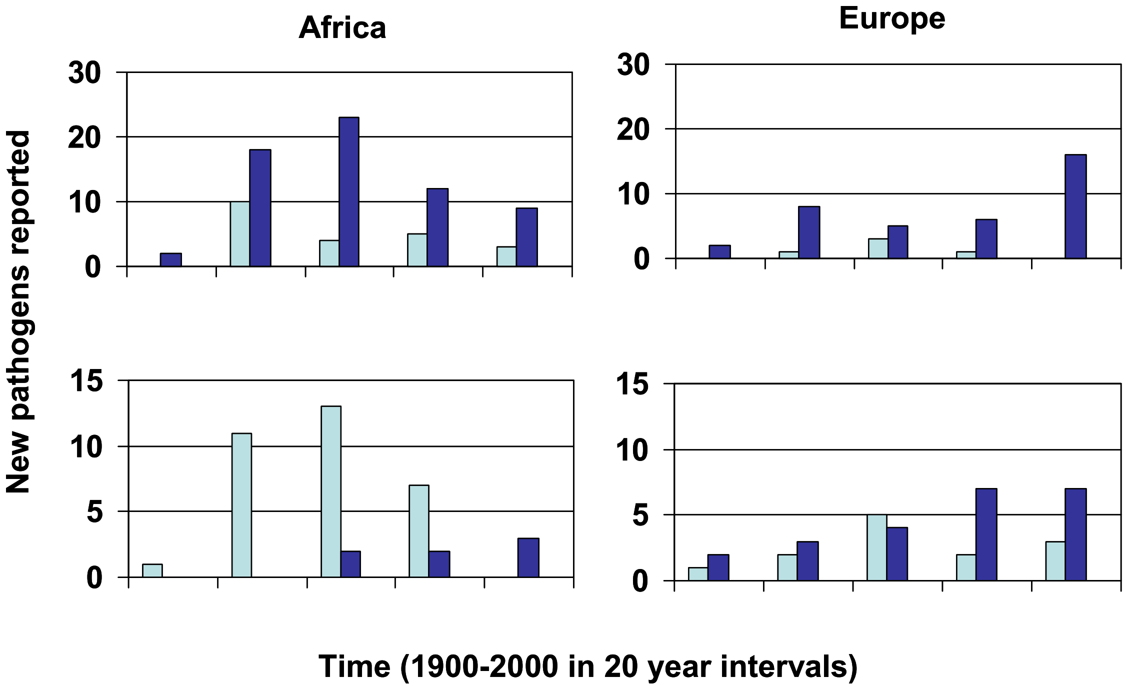

Figure 2. *Pathogen introductions reported on different plant groups for sub-Saharan Africa (left) and Europe (right), over two-decade intervals. Top: cereals (light) and other field crops (dark). Bottom: perennial fruit/nut crops (light) and horticultural/forestry crops (dark).*

The lower graphs show new disease reports on perennial tree and bush crops, and on non-food tree and horticulture crops (combined). Diseases on non-food crops constitute a greater proportion of more recent reports. This is more marked for Europe than Africa, perhaps reflecting the greater economic value placed today on environmental and amenity plantings, particularly in Europe.

There has been a distinctive change in patterns of disease reporting over the 20th century. Figure 3 shows the distribution of reports of new fungal, bacterial and viral diseases over time. For both Africa and Europe, reporting of viruses has increased as a proportion of total reports, possibly reflecting the growing awareness and diagnostic capacity for these diseases over the century.

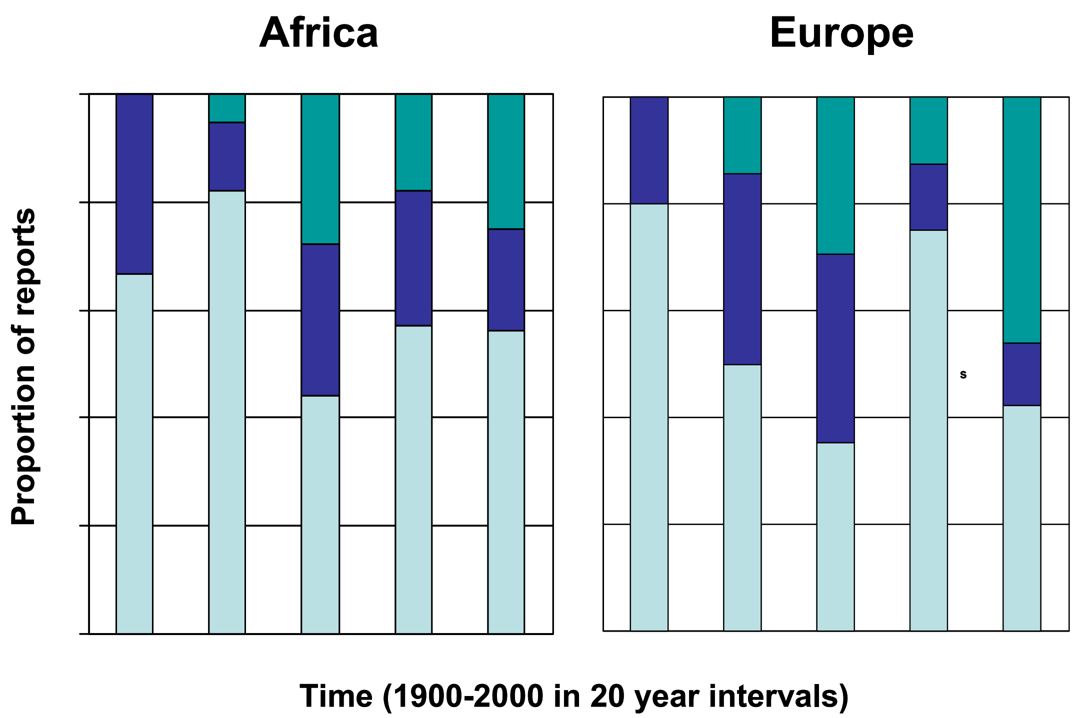

Figure 3. *Distribution of new reports across different pathogen taxa: fungi (bottom), bacteria (middle), viruses (top), as a proportion of total reports over a 20 year period*

Of course, different crop types have also supported different patterns of new disease reports. For both Africa and Europe, fungal diseases predominate on all crop types, with bacteria and viruses well represented on non-cereal field crops and perennial tree and shrub crops. Fungal diseases make up the great majority (80%) of diseases reported on cereals or non-food tree and horticultural crops.

Figure 4 illustrates the likely origin of new plant diseases reported on European and sub-Saharan African crops, and the changes in this pattern over the past century. European introductions have come predominantly from the New World, and include some diseases of east Asian origin introduced via North America, e.g. on fruit crops, trees and soybean. However, there may be a trend in recent decades towards new diseases of Old World origin. For sub-Saharan Africa, by contrast, most new disease reports indicate an Old World origin, particularly from Asia and Europe. Fewer, new diseases of likely New World origin have been reported throughout the century, but have become a greater proportion of total reports in later decades. Hence, in both Europe and sub-Saharan Africa, there appears to have been a shift towards more 'global sourcing' of reported new diseases as the 20th century progressed.

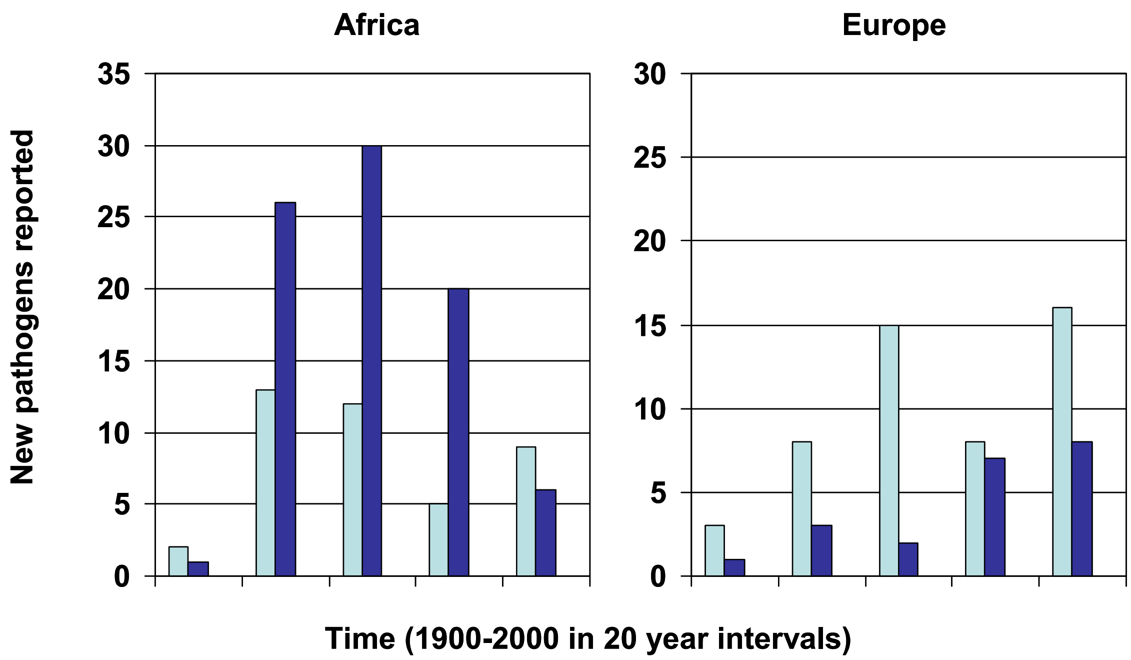

Figure 4. *New disease reports from likely New World (light) and Old World (dark) regions of origins, for sub-Saharan Africa and Europe.*

Information on the likely pathways of introduction of specific new diseases is highly variable. In many cases, reported pathways probably reflect presumptions based on the biology of the disease, rather than actual observation. Thus, while we cannot take this data to indicate the specific pathways of first disease introduction, they do give an idea of the likely pathways by which these kinds of organisms enter new countries. The most common suggested pathways include the introduction of diseases on or in seed, or on husks and other plant residues associated with seed, and the introduction of diseases with live planting material, or contaminated soil in which planting material is shipped. Of 266 new disease reports where pathways were suggested, only 35 (13%) indicated that another pathway was likely or possible. These suggested alternate pathways were often associated with particular disease/plant combinations. Fungal diseases of trees, for instance, are sometimes introduced on cut timber, while transport of insect vectors, such as whitefly, are suggested for the introduction of some viral diseases of field crops. Occasionally, a disease appears to have been introduced not on the crop affected but on another plant species, often horticultural. Importation on food or dispersal of spores by wind (between Europe and Africa across the Mediterranean) were also suggested for a few diseases.

Discussion

The observed trends in new disease reporting, and the striking differences between Europe and Africa have two possible explanations. We explore each separately below.

On the one hand, these trends may reflect the true pattern of introduction and establishment. This would mean that Africa experienced a burst of reported new disease establishments mid-century, which subsequently tailed off towards 2000, while Europe has shown a gradual upward trend over the century. For Africa, if this trend reflects true patterns of establishment, this ‘burst’ is consistent with the widespread introduction of new and improved crop varieties by colonial agricultural services early- to mid-century, and subsequently by international development assistance programmes. The comparatively high proportion of diseases reported on staple food crops in Africa *versus* Europe may reflect this development-focused process. The subsequent decline in establishments could reflect either a decline in movement of infected planting material, or better phytosanitary measures, which is certainly likely for introductions associated with development programmes. Recent decades have seen a growth in high-value horticultural exports from African countries, where we might have assumed some greater risk of disease introduction on new planting materials. However, there is no indication from this analysis that recent trade liberalisation has led to more plant disease introductions into Africa as yet.

For Europe, if we consider the trends in reported disease as true trends in new disease establishments, then our hypothesis is supported. European trends may reflect a growing level of trade, although there is no necessary causal link. It is clear that, to establish such causality, it will be important to examine changes in trade involving the actual likely pathways of disease introduction, namely planting material. In the past, correlations between new pests and diseases and agricultural trade have often been based on bulk trade, mostly in foodstuffs, including grain, but not in seeds or other planting material. We should also remember that a growing rate of establishment may reflect more species entering, or more successful establishment. Simplification of agricultural systems and their evolution towards extensive, genetically uniform monocultures has been a feature of 20th century European agriculture, which may have improved disease establishment there (Waage and Mumford in press).

However, the alternate explanation of these trends is that they reflect the level of effort expended in detection, identification and monitoring of new disease introduction and establishment. For Africa, a number of experts on African plant diseases have examined our results and suggest that the mid 20th century was a period of relatively intense taxonomic activity by plant pathologists associated with colonial and post-colonial services. These services have declined in many African countries. Structural adjustment has undermined public services such as agricultural research and extension, and other factors, including political unrest, have damaged national capacity for new disease reporting (Brownlie *et al*. 2006). In Europe, perhaps just the opposite has occurred. Greater awareness of biosecurity threats in Europe may have led to greater effort in detection, identification and monitoring, including monitoring of a wider range of plants (such as horticultural, amenity and wild plants) and hence more reports. On the other hand, heightened awareness should also have stimulated more effective prevention and fewer establishments, which is clearly not the case.

Unfortunately, both explanations are backed by good circumstantial evidence, and it is therefore difficult to suggest a single conclusion, relative to our hypothesis. However, while there has probably been a decline in new disease reporting in Africa, it is unlikely that important new diseases of crops will go undetected for many years. Similarly, European reporting of new diseases has been good for some decades. For this reason, we tentatively conclude that the rate of new disease establishment has been growing in Europe over recent decades, but not in Africa. If a future development strategy for Africa means a dramatic increase in international trade, as suggested for instance in the report of the Commission for Africa (2005), Africa may be on the cusp of a second burst of new disease challenge.

In both continents, there have been changes in the origin of new disease reports (Figure 4) which suggests a gradual globalisation of 'pathogen sourcing', and a growing diversity in the kinds of diseases reported (Figure 3), with a particular growth in reported viral diseases over the last century. Hence, the potential species pool, from which new pathogen species introductions into these regions is drawn (Waage et al. 2005), appears to be growing for Europe and Africa, and this may be a reflection of globalisation processes. For Europe, 'environmental invasions', for instance diseases of wild and amenity trees are of growing concern as the value placed on environmental conservation rises. This explosion of new important 'host plants' also greatly diversifies the species pool for future plant disease threats (Waage et al. 2005).

Before concluding, it is important to stress that introductions of new pathogen species and strains are not the only mechanisms for new disease emergence (Parker and Gilbert 2004). A recent survey of the drivers of new plant disease emergence worldwide, based on a search of the ProMED database, 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. Native diseases can shift onto introduced crops, a pattern particularly common in Africa, including with such important diseases as cocoa swollen shoot virus and cassava mosaic virus (Thresh 2006). Local pest and disease evolution interlink with the introduction of new species where introductions add new genotypes which introgress with local strains. Hybridisation 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 various mechanisms of new plant disease emergence and the factors that drive these.

Conclusions

This study has revealed dramatic trends in reporting of new diseases of crops over the 20th century in Europe and Africa, and striking differences between the two. Our hypothesis, that reported establishments should be increasing in recent years as a possible consequence of globalisation, is borne out for Europe, but not for Africa. Differences in effort in reporting of diseases may explain this result as well as it is likely that African reporting systems have declined in recent decades due to falling resources and expertise. Even considering this possibility, it is likely that the true pattern of disease introduction and establishment has been different between these regions.

For Africa, whether disease introduction and establishment has been declining over recent decades, or whether it has gone unreported due to poor detection, identification and monitoring systems, the continent may be due for a dramatic increase in new disease problems as agriculture is directed in future towards diversification for international markets and trade and traffic in planting material with other continents grows.

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