Climate modelling and pest establishment

Climate-matching for quarantine, using CLIMEX

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Summary

The role of climate-matching is described in relation to pest risk assessment. A worked example is presented, using the CLIMEX model on the Queensland fruit fly, *Bactrocera tryoni*. The potential for population growth of the Queensland fruit fly in Australia is described, together with the climatic factors which limit the geographical distribution and abundance of the species on that continent. Projections are then made of the likelihood of permanent establishment of an accidental infestation in Los Angeles. The area of north America that would be put at risk of colonization by such an introduction is then estimated.

Introduction

The primary aim of a quarantine service is to minimize the cost of pests and diseases to the target country. This is done principally by preventing their entry or export in the first place. Both imported and exported goods can require clearance to protect local agriculture or public health in the former case, or export markets in the latter case. Internal quarantine and eradication of established pests are further measures that are available.

The risks of establishment of a given pest at a particular geographical location depend on having a source of infestation, a means of transport and on a number of environmental conditions at the point of arrival, such as the climate, shelter and suitable host plants (Hopper and Campbell 1989). In addition, the attributes of the pest itself, such as its dispersal ability and the minimum initial population size which is needed to enable colonization, need to be taken into account. The efficiency of quarantine measures at both ends of the transport route are also important. Any pest risk assessment needs to take all these factors into account.

CLIMEX is a climate-matching program developed by Sutherst and Maywald (1985), Maywald and Sutherst (1989, 1991). It was designed, among other things, to help regulatory staff evaluate the risk of establishment of exotic species in relation to climate. To see how CLIMEX has been tailored to meet the needs of the quarantine community, we need to review the users' aims and requirements from information systems. Geographic Information Systems (GIS) and Expert System technology are needed to complement CLIMEX in a comprehensive pest risk assessment package, as described by Sutherst, Maywald and Bottomley (in press).

The typical quarantine service's requirements of a climate-related information system are:

i) To give a global, geographical perspective.
ii) To apply to many species in a general way, rather than a few species in great detail, i.e. the system must be generic in nature.
iii) To estimate the likelihood of successful permanent or temporary establishment of an exotic pest or disease under defined geographical and seasonal conditions.
iv) To give the likelihood of an exotic introduction multiplying to economic threshold levels or those damaging to health.
v) To give some insights into the climatic factors that determine the likely success or failure of an exotic introduction.
vi) To answer "what if" questions in relation to exotic and endemic species under different climatic scenarios, such as those associated with the mooted "Greenhouse Effect" (Sutherst 1990).
vii) To present information in a form that is readily interpretable by decision-makers. Such people are not specialists on particular species, but deal with diverse pest and disease problems.

Some examples of the specific questions which quarantine authorities like answers to are:

i) Can the species colonize all or part of the target area? If so, what areas are most at risk and what is the relative risk in different areas and seasons?
ii) If the species is introduced, will it be able to breed temporarily, or colonize the area permanently? What is the likely relative population size and will it reach economic injury levels or be restrained by marginal climates to low and variable population densities?
iii) What climatic factors limit the distribution and abundance of the species in different parts of the target area? How do these vary from season to season and from year to year? What will be the effect on the target species of climate change resulting from the Greenhouse Effect?
iv) What are the chances of successful eradication of a pest in relation to the climate in a target area?

Use of CLIMEX for quarantine

CLIMEX is designed for use on any biological entity, such as a species, breed or even ecosystem. Its primary function is to describe the suitability of the climate for any such entity at any geographical location. It does this by generating a set of indices, illustrated by an example using the Queensland fruit fly, *Bactrocera tryoni* in Table 1. The values of each parameter are estimated by inference from maps of the geographical distribution and commentaries on the relative abundance of the species in different parts of its range. Further details of the fitting procedures are given below. In the case of the fruit fly the maps of Drew, Hooper and Bateman (1982) were used and details will be described elsewhere. The indices describe the following features of the target organism, most usually a species:

a) *Population growth in the "growth season"*, described by weekly "Growth Indices" (GI), scaled between zero and one, which is analogous to the "intrinsic rate of population increase". The annual potential for population growth is described by an annual growth index, which is the sum of the weekly values, scaled between zero and 100.
b) *Persistence of the population through the unfavourable season*, with one or more stressful conditions. These may be excessive cold, heat, dryness or wetness, each described by separate "Stress Indices", denoted as CS, HS, DS and WS respectively, and scaled between zero and 100.
c) *Permanent colonization of the species and propagation of damaging populations*. An "Ecoclimatic Index" (EI), scaled between zero and 100, integrates the annual growth and stress indices to describe the overall favourableness of the location for permanent colonization.

As a tool designed for a wide range of users with different skills and applications, CLIMEX has to be versatile and user-friendly. We believe we have achieved this by paying particular attention to the following points:

1) *Easy access and operation.* CLIMEX is available for IBM compatible PC's and for Vax computers. The PC version is menu-driven, while the Vax version relies on a dialogue with the user.
To minimize the scope for error and to automate manual tasks, CLIMEX has inbuilt facilities for editing existing files of parameter values for a species or for developing such files for new species. In addition, there is an option for managing the large meteorological database.
2) *Flexibility of operation.* Quarantine incidents can involve species for which the user has extensive information or ones for

Table 1. CLIMEX[1] parameter values that give the best visual fit to the distribution of *Bactrocera tryoni* in eastern Australia.

Moisture parameters		
SM0	Lower threshold of soil moisture	0.05
SM1	Lower limit of optimal range of soil moisture	0.50
SM2	Upper limit of optimal range of soil moisture	2.0
SM3	Upper threshold of soil moisture	4.0
Temperature parameters		
DV0	Lower threshold of temperature for population growth	14.0°C
DV1	Lower optimal temperature for population growth	31.0°C
DV2	Upper optimal temperature for population growth	35.0°C
DV3	Upper threshold temperature for population growth	40.0°C
Stress indices		
SMDS	Soil moisture dry stress	0.25
HDS	Rate of accumulation of dry stress	0.002
SMWS	Soil moisture wet stress	2.0
HWS	Rate of accumulation of wet stress	0.002
TCS	Threshold of cold stress (day-degrees)	25
HCS	Rate of accumulation of cold stress	0.0001
THS	Threshold of heat stress	36
HHS	Rate of accumulation of heat stress	0.05

[1] See Sutherst and Maywald (1985) and Maywald and Sutherst (1991) for further explanation.

which there is very limited knowledge. The most common situation is where the user knows the existing geographical distribution and seasonal incidence of the species, but has little biological information. For most practical purposes observations on the geographical distribution are the most useful source of information with which to estimate the limiting effects of climate on a species. The climatic tolerances of the species are inferred from the field observations and are described by the stress functions of the CLIMEX model. The values of the stress indices are estimated by an iterative process, with progressive adjustments until the CLIMEX predictions agree with the observed distribution. Naturally this procedure is based on the assumption that climate, directly or indirectly, limits the present geographical distribution of the species. This is not always true (Sutherst 1987). Appropriate caution and use of other sources of information is therefore advisable. The population growth indices are estimated from information on relative abundance and seasonal incidence in different parts of the species' geographical distribution.

Sometimes the information for a species is not adequate to fit the model parameter values with confidence. The CLIMEX "match climates" option then remains to match the climates in places of interest directly with those in other places where the species already exists. As more detailed information becomes available, the values of the various functions can be fine-tuned to increase their precision. Eventually, adequate data may justify the development of a population model to address more specific issues.

3) *Presentation of results*. A great deal of attention has been given to the formats for presentation of the results. They give a range of detail to meet the diverse needs of policy makers through to specialist users, such as research workers. The nature of quarantine activities results in the generation of reports for numerous species. To minimize repetitive tasks and help the user to digest the information from CLIMEX, a report generator has been included. The CLIMEX reports are in natural language and give a preliminary interpretation of the estimated parameter values and of the results. Selected maps and graphs are integrated into the report on request. The report summarizes the most frequently occurring stress factor limiting the species in the target area.

CLIMEX relies on maps and graphs to tell the story simply. Examples are given, using the Queensland fruit fly, *B. tryoni*, to illustrate firstly, an internal quarantine problem and secondly, a potential threat to another continent.

In the first example (Figure 1a-f), the values of EI, GI, the active stress indices and the number of day-degrees above the developmental threshold temperature are mapped for Australia, where the species is endemic on the east coast. The maps give a continent-wide perspective of the response of this fruit fly to the Australian climate. The results are in broad agreement with those of Meats (1981), although they were derived without recourse to experimental data on the life-cycle.

The second example shows the chances of establishment of the fly in Los Angeles (Figure 2) and the consequent threat posed to the rest of north America. Population growth in Los Angeles is limited by dryness in summer, but temperatures are very favourable. The graph shows that extensive irrigation would be needed for the species to prosper there. Given such an environment, the low values of the stress indices for the location, as shown in Table 2, indicate that the fly could survive there permanently. The fly's potential performance in a few other north American locations is also given in Table 2. The area of the continent at most risk is readily identified in Figure 3. as the eastern seaboard from Florida to New York and west to Kansas, Oklahoma and Texas

CLIMEX also tabulates the climatic indices for each location in a variety of formats with varying amounts of detail. An example, with a selection of north American locations to illustrate the occurrence of different potentials for population growth and of different degrees of limiting "stress" factors on the Queensland fruit fly, *B. tryoni*, is given in Table 2.

Table 2. Results of a CLIMEX simulation to estimate the risk from the Queensland fruit fly, *Bactrocera tryoni* to fruit in selected locations in north America.

				Stress Indices				
Location	Rain	Day-degrees	Growth index	Cold	Heat	Dry	Wet	Ecoclimatic index
Austin	862	2534	26	22	0	1	0	20
Jacksonville	1334	2637	43	13	0	0	0	37
Lethbridge	384	406	2	145	0	0	0	0
Los Angeles	233	1428	2	23	0	27	0	1
New York	1086	1064	17	83	0	0	0	3
Ottawa	872	575	8	122	0	0	0	0
San Francisco	563	412	2	473	0	7	0	0

Discussion

Several national and international organizations are using CLIMEX to estimate the likelihood of colonization and later success of pest species (Sutherst and Maywald 1985, Walker and Olwage 1988, Worner 1988, Sutherst *et al.* 1989, Halliday and Sutherst 1990), diseases (Sutherst and Maywald 1987, Lessard *et al.* 1990) and also beneficial organisms (Worner *et al.* 1989, Tyndale-Biscoe 1990). Lessard *et al.* (1989) incorporated CLIMEX into a Geographic Information System (GIS) to combine

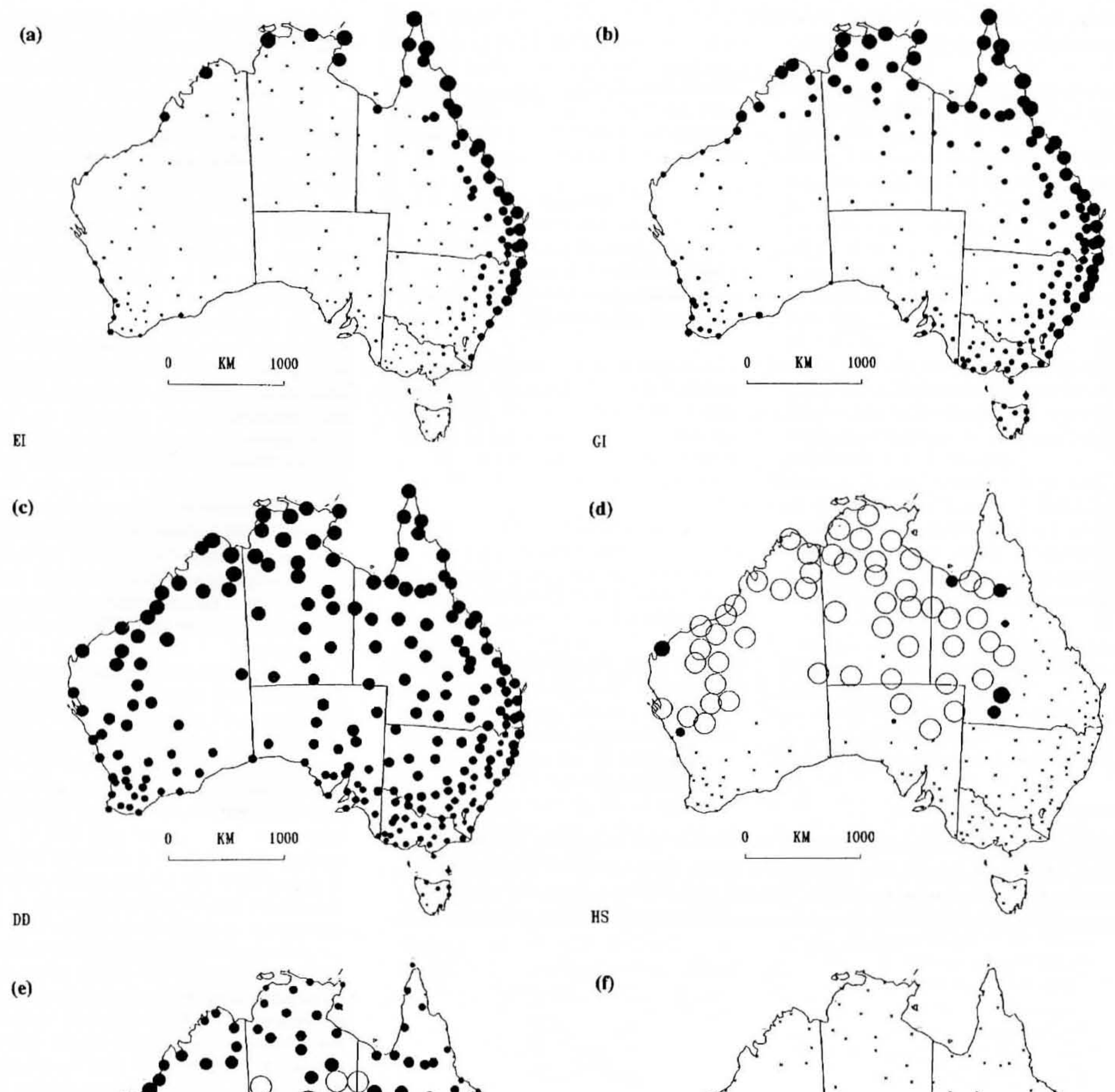

Figure 1. CLIMEX indices describing the response of the Queensland fruit fly, *B. tryoni* to climate in Australia. (a) Ecoclimatic Index (EI) - favourableness for permanent colonization, (b) Growth Index (GI) - favourableness for population growth, (c) day-degrees of temperature above 12°C, (DD), (d) Heat Stress (HS), (e) Dry Stress (DS), (f) Cold Stress (CS). Wet stress (WS) is not indicated as having any severe limiting effect on the fly. The area of the circles is proportional to the value of the index. When the values of the stress indices in (d), (e), and (f) exceed the maximum tolerable level of 100, the shading is omitted from the circle.

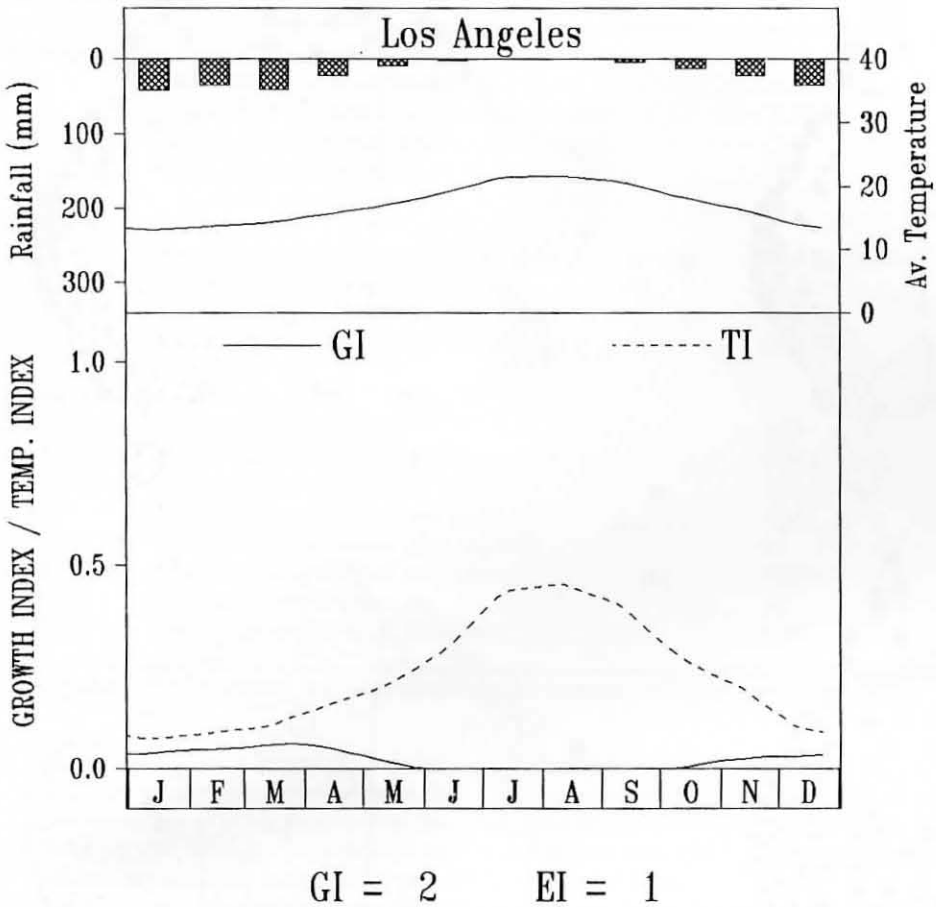

Figure 2. Seasonal favourableness of the climate of Los Angeles for the Queensland fruit fly, *B. tryoni*. The broken line shows the response of the fruit fly to temperature (Temperature Index, TI) and the solid line shows the combined response to temperature and moisture, as described by the Growth Index (GI).

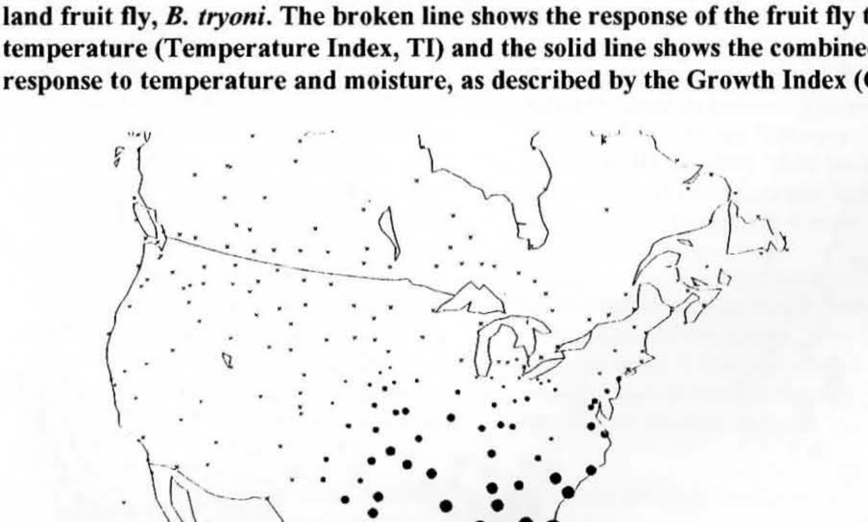

Figure 3. The potential North American distribution of the Queensland fruit fly, *B. tryoni* should that species be introduced into that continent. Crosses indicate failure to colonize permanently. The areas of the circles are proportional to EI, the index of favourableness of the climate for permanent colonization.

the effects of climate with other geographical variables determining the risk from the livestock tick-borne disease, East Coast fever.

CLIMEX provides preliminary insights into the climatic conditions which favour population growth or decline. These can be helpful as part of a detailed ecological study (Sutherst and Maywald 1985) and to identify climatic causes of pest outbreaks. For example, CLIMEX was used to identify the parts of Africa with stressful conditions for cattle which allow tick numbers to increase (Sutherst and Maywald 1987). Environments with long annual dry seasons appear unfavourable for tick development and survival, but they favour the build up of large tick populations as the nutritional stress causes their cattle hosts to lose their resistance. Hence, interpretation of the results needs care to separate the direct and indirect effects of climate on the target species.

Annual variation in climate is also an important cause of changes in the geographical distribution of animals. CLIMEX has the facilities for comparing a series of years in the same place as well as for more general comparison of scenarios based on defined levels of variation in climate.

There is a range of tools available for matching climates. They range from tables and graphs to computerized packages such as CLIMEX and BIOCLIM (Busby 1985). BIOCLIM compares the values of meteorological variables on a quarterly basis and produces an "envelope" of values for a given species. It therefore emphasizes the meteorological side of the problem. CLIMEX is a dynamic model which integrates the response of the species weekly, and derives indices which incorporate these responses in a readily interpretable form. It can thus describe seasonal changes in suitability and help identify the nature of limiting factors such as coldness or dryness in different environments. CLIMEX therefore describes the climate as experienced by the species concerned. CLIMEX can also be made to detect periods of severe stress as short as one week, while BIOCLIM is limited to quarterly intervals. While BIOCLIM is less informative about the dynamics and nature of climatic factors affecting a species, fitting procedures for estimation of parameter values require less skill. Fortunately CLIMEX is insensitive to most small changes in parameter values and is much more user friendly and produces much more readily interpretable results.

Both approaches have much to offer in the field of climate-matching and both suffer the same limitations that are inherent in such activity. These are firstly, the effects of undetected, non-climatic, limiting factors which cause errors in estimating climatic limits. Secondly, the lack of a full spectrum of climates in the area of origin of the target organism also results in some climatic limiting factors being undefined. For example, in the current example with the Queensland fruit fly, there is nowhere in Australia with as severe winter temperatures as those experienced in north

America. Hence the limiting effect of minimum temperatures has to be inferred from other observations.

Conclusions

Questions relating to the establishment of exotic species are currently acquiring a greater importance in the context of global attempts to remove artificial quarantine barriers to international trade. Accidental introductions of pest species will continue to require a response from quarantine authorities. CLIMEX provides the opportunity for future responses to be based on more objective estimates of risk in relation to climate than has been possible in the past. The PESKY expert system, linked to CLIMEX and a GIS package offers the prospect of a powerful and comprehensive approach to global risk assessment, which can be used to take account of climatic, geographical and management related issues in the context of the particular situation being investigated (Sutherst, Maywald and Bottomley in press).

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