Use of CLIMEX in Pest Risk Analysis for Quarantine

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April 2004

To run the specially prepared CLIMEX demo, select **CLIMEX demonstration** from the **Library** menu.

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1. Introduction

The WTO (World Trade Organization) has adopted pest risk policies that are implemented by the International Plant Protection Convention (IPPC), which is a multilateral treaty deposited with the Director-General of the Food and Agriculture Organization of the United Nations (FAO) and administered through the IPPC Secretariat located in FAO's Plant Protection Service. WTO members are encouraged to base their measures on international standards, guidelines and recommendations where they exist. However, members may maintain or introduce measures that result in higher standards if there is scientific justification or as a consequence of consistent risk decisions based on an appropriate risk assessment (for more information, see the ***SPS Agreement***).

The primary aim of national plant and animal protection services is to minimise the cost of pests and diseases to the target country. This is done principally by preventing the entry of exotic species with appropriate quarantine procedures. Both imported and exported goods can require clearance to protect local agriculture or public health. Internal containment and eradication of exotic pests that breach the barriers are further measures that are available and need a knowledge of the species' environmental requirements.

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 favourable environmental conditions at the point of arrival, such as the climate, shelter and suitable host plants. In addition, the attributes of the pest itself, such as its reproductive rate, dispersal ability and the minimum initial population size that is needed to enable colonisation, strongly influence its chances of establishment. The efficiency of quarantine measures at both ends of the transport route is important. Any pest risk assessment needs to take all these factors into account.

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1.1 *CLIMEX*

CLIMEX (**http://www.ento.csiro.au/climex/climex.htm**) is a decision-support system developed by Sutherst and Maywald (1985), in part, to help users to evaluate the risk of establishment of exotic species in relation to climate. Further information on CLIMEX theory and operation can be found in Sutherst *et al.* (1995, 1999a), and Sutherst (1998, 2003, 2004). CLIMEX is now used routinely to define the climatic context for interpretation of local information on species prior to an ecological study. Examples of the many applications can be viewed at **http://www.ento.csiro.au/climex/bibliography.htm**. The inference-based approach used in CLIMEX exploits the exquisite ability of biological organisms to integrate all of the environmental influences acting on them in any given location. This integration results in all of the environmental influences and varying sensitivity of different instars being automatically reflected in the distribution, phenology and relative abundance of the species. CLIMEX is therefore applicable to any species of pest, regardless of the amount of information available on it. Indeed, the model has been very successful when used on a range of species for which only the geographical distribution is available, to others for which sophisticated population models exist. CLIMEX has always provided new insights into the species' performance in different environments. As more data become available, the parameter values can be fine-tuned and confidence in the model projections increased accordingly.

1.1.1 *History and concepts*

CLIMEX was conceived in the early 1980s to create an over-view of the climatic requirements of pest species for which a minimum of data was available. The specific trigger was an urgent request for urgent advice on the risk posed by an outbreak of the livestock tick *Haemaphysalis longicornis*, in a tick-free area of Western Australia. The need was bolstered by initiation of a 3-year study of the ecology of the buffalo fly, *Haematobia irritans exigua*. The authors recognised that the laborious procedures involved in matching climates could be automated using computers. They assumed that climate was the most important factor limiting the geographical distribution of arthropod species in their continents of origin. Further, they assumed that climate was the dominant force determining the underlying patterns of seasonal phenology and relative abundance of a species in any given location. Every species was likely to have its own unique climatic requirements, so the value of regional classification methods was limited.

Most places, apart from a few tropical areas with either constant conditions (Amazon) or with two rainfall seasons each year (East Africa) have one season that is suitable for population growth and another that is unsuitable (Sutherst and Maywald, 1985). A useful decision-support system needed to capture these two different features of any given location if it was to be globally applicable. An overall index was also needed to describe the potential of a given location for continuous population persistence and growth. It is also an advantage to be able to identify the particular climatic limiting factors that determine the boundaries of the geographical distribution in different directions. These needs spawned the CLIMEX concept. It combines different indices that describe population growth and persistence.

The ‘Growth’ index, originally devised by Fitzpatrick and Nix (1970) to describe physiological-level processes in crop growth and used by Gutierrez *et al.* (1974 a, b) in an ecological study of aphids, was adopted but without the compulsion to use physiological data. Growth conditions are inferred from seasonal data on the growth of the populations and the index is analogous to the "intrinsic rate of population increase", which is familiar to all ecologists. We recognised that the climatic conditions favouring population growth could be inferred from the climate at times when the species was increasing in abundance. These times can be identified from population census data in different places, and the conditions described by a weekly "population growth index" (GI) based on temperature, moisture and daylength and scaled between 0 and 1. Annual mean growth indices are scaled between 0 and 100. Favourable conditions can also be inferred from the relative abundance of the species in different parts of its geographical range.

A series of ‘Stress’ indices describe the duration and intensity of extreme climatic conditions, which limit the ability of the species to persist in a given location. Gutierrez *et al.* relied on the absence of suitable growth conditions to infer the limits to the geographical distribution, but that process does not provide a mechanism for investigating the duration and intensity of extreme conditions that cause a population to die out. Thus it could not be used on migratory species for example. In addition, it relied on extensive experimental measurements that are rarely available when dealing with exotic pests. CLIMEX explicitly estimates the limiting conditions by inferring the values of parameters for each stress function (hot, cold, wet, dry) from the gradients in climatic elements towards the boundaries of the distribution in different directions within the geographical distribution of the species in its endemic area. This provides a powerful tool for exploring different hypotheses about the mechanisms that limit geographical distributions, without the need for experimental data, except for validation purposes if required.

The annual potential of a given location or year for population growth is combined with the severity of stresses which depress the size of that population in the unfavourable season, to give an overall measure (the "Ecoclimatic Index" (EI) on a scale of 0-100) of the favourableness of the location or year for the species.

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1.2 *Use Of* CLIMEX *for quarantine*

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. A climate-related DSS for pest risk analysis needs to include the following functions:

- To provide a global perspective of the risks posed by a given species.
- To be generic and general rather than specific and detailed, so that it can apply to many species, rather than to a few key species
- To estimate the likelihood of establishment of an exotic pest or disease under defined geographical and seasonal conditions.
- To estimate the risk of an exotic pest causing economic damage or public health injury.
- To identify the climatic factors that determine the likely success or failure of an exotic introduction.
- To address "what if" questions in relation to exotic and endemic species under different climatic conditions.
- To present information in a form that is readily interpretable by decision-makers, who deal with numerous and diverse pest and disease problems.

As a tool designed for a wide range of users with different skills and applications, CLIMEX has to be versatile and user-friendly. Particular attention has therefore been given to the following points:

1. Easy access and operation. CLIMEX runs on a Windows platform and has been adapted to run under UNIX, but the latter version is not in high demand.
2. CLIMEX has in-built editing facilities to create or edit files of parameter values that describe the response of a species to climate. Each file constitutes the CLIMEX 'model' for that species, and CLIMEX can therefore be considered to be a model building package rather than a model per se. The large meteorological database can also be edited or supplemented by individual users.
3. Flexibility of operation. Quarantine incidents can involve species for which the user has extensive information or ones for 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. The inferential procedure is based on the assumption that climate, directly or indirectly, limits the present geographical distribution of the species. This is not always true. Appropriate caution and use of other sources of information is therefore advisable.
4. Sometimes the information on a new target species is insufficient to allow the model parameter values to be estimated with confidence. This is the usual case when dealing with biological control agents. The CLIMEX "*Match*

Climates" option enables the climate in a location of interest to be compared with those in other places.

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2. Using CLIMEX

2.1 *Precautions*

Before attempting to create a model to describe the responses of a species to climate, we need to ensure that climate plays a significant role in the species lifecycle. Therefore it is necessary to address some non-climatic issues before fitting a model. Some issues are raised below in an attempt to prompt CLIMEX users to question the role of such factors.

2.1.1 *Attributes of target species*

There is a wide range of sensitivity of species to climate. Depending on the biology of the species, it may be directly exposed to climate, or be sheltered from direct effects. Before proceeding with a CLIMEX analysis, we need to clarify whether the species is affected by climate to the extent that its distribution may be determined largely by climate. The lifecycle of the species will indicate the extent to which it is likely to depend on climate for its propagation and persistence. For example, viruses that are transmitted in seed may not be affected by climate, except when they are in other stages of their host plant, and so there may not be any definable climatic range beyond that of the host plant. The sensitivity of vector-borne diseases to climate depends also on the sensitivity of the vectors, so any analysis of plant or animal vector-borne diseases must include an assessment of the role that the climatic requirements of the vectors plays in limiting the distribution of the disease.

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2.2 *Barriers to geographical distributions of species*

2.2.1 *Non-climatic barriers*

Reliance on an inferential approach to estimating responses of species to climate, based on observed geographical distributions has a number of weaknesses that users need to be fully aware of. The limitations of the approach demand that documentation of models built using CLIMEX must include suitable caveats in relation to a number of potential non-climatic limiting factors (Sutherst and Maywald, 1985).

2.2.1.1 *Physical barriers*

Examination of Fig. 1 reveals that the increasing moisture gradient continues into coastal areas in both the northeast and southeast of North America. Thus, any species that lives in these areas can be assumed to tolerate high soil moisture conditions. However, if that species exists on the coast there is no way of inferring how much wetter conditions it will be able to tolerate. In this case the limit set by wetness will be undefined and will need to given some assumed value.

Such coastal barriers are common and necessarily reduce the confidence in estimation of the climatic limits for a species, although usually this is not a serious problem. Other types of barriers include large mountain ranges such as the Himalayas, which present an abrupt barrier between temperate and tropical parts of Asia.

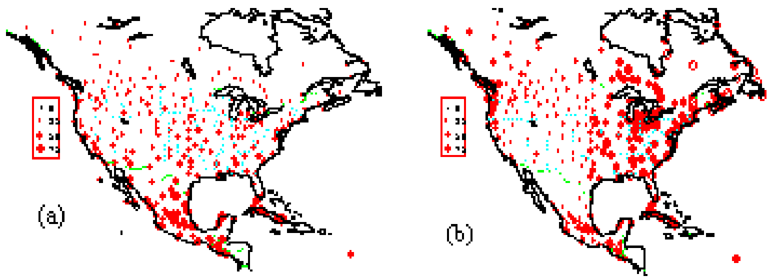

Fig. 1. An example of the use of the CLIMEX _*Climatic Gradients Utility* for (a) temperature and (b) moisture in North America. The circles are proportional to the total annual heat load or soil moisture respectively.

2.2.1.2 *Hosts*

Numerous host-specific species are limited by the availability of their hosts, so the challenge is to separate the limitations of climate on the host from the direct effects of climate. If the geographical distribution of a predator covers the full range of its host there is no means with which to infer its climatic responses to limiting conditions. In such cases, the best that can be done is to model the potential range of the host in relation to climate.

2.2.1.3 *Other species*

Every species exists in a community of species and it will interact with many of them. Usually that will affect the relative abundance of the species within its geographical range, but sometimes, endemic species will prevent exotic species from establishing. The literature has many examples of parapatric boundaries between closely related species and Sutherst and Maywald (1985), in their original description of the CLIMEX model, described how an African species of tick, *Boophilus decoloratus*, has prevented the colonization of much of sub-Saharan Africa by the related Asian species, *Boophilus microplus,* for decades. In this case the potential distribution of the latter species was inferred from its distribution in Australia, and subsequent events have shown that it is rapidly colonizing the area that was defined as at risk in 1985. Hence such biological interactions cannot be assumed to act as permanent barriers when the context changes.

Clarification of the role of other species is crucial if the climatic limits of a species are to be defined correctly. In this regard it is equally important to recognize that the CLIMEX model attempts to define the species' responses to each climatic variable so that the inferred geographical distribution matches the observed distribution. By including all reliable positive records, it defines a climatic range that may sometimes include areas not colonized by the species. In such cases, where there is an apparent discrepancy between the observed range and that inferred by CLIMEX, it is essential to test possible explanations. In Africa for example, CLIMEX has been used to infer the potential ranges of several species of ticks that have subsequently expanded their ranges, by being carried on moving livestock, to new areas on that continent that were previously identified as high risk from CLIMEX analyses. This approach differs greatly from the alternative statistical methods.

2.2.1.4 *Artificial environments*

Agriculture and horticulture strive to increase the yield of crops by overcoming the natural hazards that wild plants experience from the climate and competitive plants. In providing a sheltered environment for their crops, humans also alter the environment for crop pests. Thus a pest risk assessment needs to consider the effects of practices, such as irrigation or use of glasshouses, on the distribution and abundance of pests. Field observations on pest occurrence need to be scrutinized carefully to exclude records that alter the natural distribution. In the case of irrigation, CLIMEX contains an irrigation scenario builder to allow the user to assess the effects of different irrigation practices on pest distributions. When glasshouses are involved, there is no established method of predicting their effect on the distribution and a suitable caveat is needed in any risk assessment. The example of *Bemisia tabaci* (B biotype) in the demonstration of CLIMEX illustrates the issue.

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3. Building CLIMEX Models

CLIMEX is unique in that it is an inferential or 'inverse modelling' tool, which relies on model building processes that are the opposite to the traditional, reductionist mechanistic modelling paradigm. Combined with this unconventional approach, CLIMEX also relies on data sets – in the form of observed average geographical distributions – that lack precision. CLIMEX is deliberately designed to present information in graphical and map formats that convey the lack of precision involved in country to continental scale analyses. These features indicate that CLIMEX has a pragmatic approach that is designed to make the best use of available information; rather than deferring an assessment until a comprehensive set of data can be accumulated. For these reasons, some potential users develop a sense of anxiety and frustration when using CLIMEX. Users need to appreciate that they are creating a model that is intended to capture the gross responses of a species to climate, in order to set the global context within which to conduct local studies. As once described by a user, '*CLIMEX sees our problems as if from an aeroplane*'. In the absence of non-climatic inputs into the CLIMEX models, which do not describe lifecycle processes, it is not possible to depict a species' population dynamics or to use the model to design detailed management options. These need mechanistic models.

In the following paragraphs a procedure is suggested for fitting the parameter values for the CLIMEX model, given the usual situation where little data is available beyond an observed distribution and perhaps some observational data on field population densities. It is assumed that the user has eliminated or otherwise accounted for the non-climatic factors discussed above.

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3.1 *Identifying climatic gradients*

Effective operation of the CLIMEX model demands that the user has a workable knowledge of the climates around the world. Such knowledge allows us to identify climatic gradients within the region that is being used to estimate parameter values for a given species. CLIMEX provides a '_*Climatic Gradients Utility*' to facilitate the detection of temperature and moisture gradients. It can be used to map relative values of the annual soil moisture and the annual heat load experienced at each location. Of necessity, due to the nature of the temperature and moisture functions that contribute to the CLIMEX 'Growth Index', the utilities provided are arbitrary in nature but nevertheless describe a direct relationship between the particular index and the variable being tracked within the levels described above.

3.1.1 *Climatic Gradients Utility*

The *Climatic Gradients Utility* has two components:

- A temperature utility
- A soil moisture utility

3.1.2 *Temperature utility*

Ideally, values for the temperature parameters need to produce a function that is directly proportional to temperature over the global range from ~ -47°C to +47°C for the monthly minimum and maximum temperatures respectively. In practice, this creates a temperature function that is insensitive to temperatures over the central part of the range where most interest lies when dealing with biological organisms. Therefore, the values of the utility parameters were arbitrarily set as follows:

DV0 = 0; DV1 = +40, and DV2, DV3 are neutralized by making their values exceed the highest temperature in the database of 46.7. Temperatures below zero are treated as equal to zero.

The *Temperature Utility* then describes the total annual heat load in a given location by creating a Temperature Index that is directly proportional to temperature. Temperatures <0°C or >40°C are assumed to equal those thresholds.

3.1.3 *Soil moisture utility*

The '_*Soil Moisture Utility*' is provided to enable CLIMEX users to estimate available soil moisture in different seasons at each location. This enables them to relate their experience and species' growth or stress levels to this derived measure of water availability, rather than to the less useful rainfall data. Soil moisture is used as a measure of available moisture in CLIMEX in the same way that water tanks store water from short-term rainfall events. Rainfall enters the store each week and evapotranspiration removes it. Different soil types store different amounts of water, so the soil model has an adjustable parameter called 'Maximum soil moisture capacity' that is set at 100 mm as default. The store can be increased to represent deep or heavy soil types or reduced to represent shallow or sandy soils, but it has to be the same for any one simulation. The ratio of evapotranspiration to evaporation from an open water source can also be adjusted using the evapotranspiration parameter in the soil moisture model. This may be desirable when using grossly different vegetation cover. As a guide, when the soil moisture goes down to 0.2 it commonly results in grasses wilting, while a value of 1.0 indicates that the soil is saturated and all further rainfall will runoff until some of the stored moisture has been transpired by plants.

As the supplied '*_Soil Moisture Utility*' parameter file is protected, users need to make a new species file and import the supplied file so that they can edit the soil and evapotranspiration parameters. All other parameters have been set either to describe the function or to neutralize their effect and no value should be altered.

The example in **Fig. 1** shows the north-south temperature gradient in North America, and the more mixed gradients of moisture tending to dryness in the southwest. The gradients provide a guide to the likely identify of factors limiting the geographical distribution of species in different regions.

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3.2 *Estimating climatic limiting factors (Stresses)*

The parameter values that define the threshold condition below or above which the species accumulates stress, and the rate at which it does so, are estimated initially. CLIMEX provides the user with a series of *Templates* with which to start the parameter fitting process when the user is dealing with a new species (see the CLIMEX Users Guide). Using a process of iteration, as described in the accompanying demonstration, the user adjusts the threshold values until the predicted distribution matches the observed distribution. With a default value of 0.001, the rate parameter can then be adjusted until the fitted distribution more accurately describes the actual distribution. Sutherst *et al.* (1995) described how the rate parameters determine the gradient of the slope of CLIMEX Ecoclimatic Index values approaching the edge of the distribution to produce a ‘ramp’ effect.

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3.3 *Estimating climatic constraints to completion of the lifecycle*

Two features of the lifecycles of temperate species have the potential to limit their distribution along a temperature gradient. Firstly, there is a need for the growth season to be long enough to allow the species to complete at least one generation per year in most species. For example, if a species needs (say) 500 degree-days above its developmental threshold temperature of 12°C to complete one generation, locations at higher latitudes or altitudes will not provide sufficient thermal accumulation to satisfy that need and the species will be excluded. CLIMEX has a parameter ‘PDD’ that allows the user to investigate the potential role of the length of the growing season on the distribution of the species. The value of the inferred developmental threshold (DV0) would be set initially at the same value as that of the Template species. If the value of PDD can be inferred from field data in association with the CLIMEX climatic database, it can be used to define cold-limited constraints to the distribution. The parameters are adjusted until the inferred range that is limited by the length and warmth of the summer corresponds with the observed geographical distribution. The model then constitutes an hypothesis that is amenable to experimental analysis. Such limits are common with crops where they are unable to complete their lifecycle and produce seed before the low autumn temperatures arrive.

A second constraint in some species is the need for obligate diapause. If conditions that trigger diapause are not met, the species is unable to survive until the next year. Similarly, many plants need chilling through a process of vernalization, to flower and so to reproduce. CLIMEX provides a 'Diapause' function to allow the user to estimate the effects of insufficient chilling on the potential geographical distribution. The parameters are adjusted until the inferred heat-limited range corresponds with the observed range. The model then constitutes an hypothesis that is amenable to experimental analysis.

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3.4 *Estimating the population growth parameters*

CLIMEX describes conditions affecting population growth using two parameters (DV1, DV2) to define a range of optimal temperatures and two parameters to define the values at which growth is no longer possible (DV0, DV3). The latter two lie adjacent to the corresponding stress parameter values, while the former are determined to be midway between DV0 and DV3, with an interval of ~4-8°C between them depending on how tolerant the species appears to be of variation in temperature and moisture, as evident from the size of the species' geographical distribution. For example, if the DV0, DV3 vales are 10°C and 30°C then the initial values of DV1 and DV2 would lie in the region of 22°C, with an initial suggested range of 17-25°C.

An iterative process is used to optimise the CLIMEX parameters to get the best fit to the observed distribution and seasonal phenology data. The model is then ready to be used in a pest risk analysis.

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4. Using CLIMEX in a Pest Risk Analysis

The risks of introduction of an exotic species arise from the infestation pressure at the *Source* location from which the commodity is being exported, the nature of the transport mechanism, and the receptivity of the *Destination*. CLIMEX is able to infer the likely pressures at each end of the translocation, at least in relation to climatic suitability. Hence, we need to run CLIMEX with data from the *Source* location/region and from the *Destination* location/region, initially. An example is given below.

Focus now turns to the *Destination* to determine the area at risk and the season when the risk is the greatest. The example in Fig. 2 shows that much of central and western Europe has Ecoclimatic Index values that exceed ~20, which has been found with some species to correlate with economic damage. By using the greenhouse scenario option in CLIMEX it is possible to investigate the sensitivity of these results to annual variation in temperature or rainfall. For example, an increase of 1.5°C results in much of Ireland becoming suitable for the Colorado potato beetle [*Leptinotarsa decemlineata*].

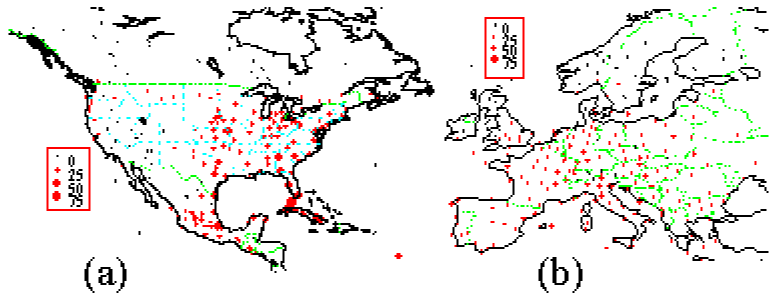

Fig. 2. CLIMEX Ecoclimatic Indices for (a) North America, the *Source* of Colorado potato beetle and (b) Europe, a *Destination* for the beetle. The circles are proportional to value of the Ecoclimatic Index.

Depending on the nature of the species involved, this value will vary, with low values being significant for severe disease vectors, and higher values applying when the economic injury threshold is quite high. If data are available on economic losses in the *Source* region, it may be possible to calibrate the Ecoclimatic Index values against those losses, as was done with the Queensland fruit fly, *Dacus tryoni,* by Sutherst *et al.* (1999b).

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6. Citations

An up to date list of citations of CLIMEX are retained on the CSIRO Entomology's CLIMEX Website: **http://www.ento.csiro.au/climex/bibliography.htm**

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