Research Article

The probable spreading and risk assessment of the corn cyst nematodes *heterodera zeae* and *punctodera chalcoensis* on maize in Belgium and the Netherlands

Abstract

A pest risk assessment (PRA), was conducted on the corn cyst nematodes *Heterodera zeae* and *Punctodera chalcoensis* on maize as host in Belgium and the Netherlands as the pest risk assessment areas where the organisms are yet to be reported due to potential phytosanitary concerns that their introduction to this areas might cause financially to corn. To assess the potential geographic distribution of the pests in the study areas and other areas in Europe out of its present areas of occurrence, two tools were used for the study; CLIMEX, a computer simulation model and the European and Mediterranean Plant Protection Organization's Pest Risk Assessment guidelines to see if the pests can be introduced and established in the areas under consideration. Geographic distribution data for *H. zeae* in its current locations were used to fit parameter values in the CLIMEX program. In the case of *P. chalcoensis*, since the environmental requirements are unknown, the 'match climates' function, which allows for the comparison of the different climates of different locations on the globe, was used. The CLIMEX analysis suggests that H. zeae, being a tropical species cannot become established in Belgium and the Netherlands because of the cooler climate in these areas, however its effect becomes more evident in the southern parts of Europe. It is therefore recommended that this relatively dangerous cyst nematode be placed first on the mentioned alert list for quarantine-organisms as a potential quarantine organism. The analysis also showed that *P. chalcoensis* has the potential to become established in both Belgium and the Netherlands as well as much of the European continent and could thus be placed on the European and Mediterranean Plant Protection Organization's alert list or quarantine list of organism, although the possibilities of its introduction in the PRA areas is very low. However, before adding it to the alert or quarantine-lists, the organism's biology (i.e. temperature requirements) should first be studied. Both pests should not only be placed on the alert list of the PRA areas, but also on the alert list of potential quarantine-organisms of all the countries world-wide that are at potential risk upon introduction of the pests. The conclusion from the study was based on the combination of the results from both CLIMEX and the PRA guidelines since the use of only one may not give very reliable results.

Keywords: *heterodera zeae*, punctodera chalcoensis, CLIMEX, pest risk assessment, maize, simulation model, parameter fitting, degree-days

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Abbreviations: PRA, pest risk analysis; EPPO, european and mediterranean plant protection organization; PDD, degree-days per generation; EI, ecoclimatic index

Introduction

The corn cyst nematode *Heterodera zeae*,[1] was first detected on the roots of maize collected from Rajasthan, India.[1–3] The pest has subsequently been reported to be present in Pakistan.[3–5] Thailand,[2,6] Egypt,[7] Greece.[8] Portugal[9] and Virginia and Maryland in the USA[2,10,11] *Heterodera zeae* is restricted to warmer tropical and sub-tropical areas. And its distribution can be seen in Figure 1A. The corn cyst nematode is a sedentary semi-endoparasite feeding on plant roots and has been associated with significant yield losses of between 21 and 73% in infected maize.[12] Above ground symptoms are often characterized by isolated patches of unhealthy plants that are stunted and pale colored.[13] The damage caused by the pest is more profound under hot and dry conditions.[14] The nematode colonizes the roots of its host, producing tan colored, lemon shaped cysts that are visible on the roots of infected plants.[15]

Heterodera zeae predominantly affects maize crops, however it has also been reported on a large number of other host plants, including grains, fodder and weed species in the Gramineae family.[10] Because of the wide host range of *H. zeae*, it is important to select crop rotations carefully in order to minimize population increase.[16]

Shanina et al.,[17] found the minimum time required for *H. zeae* to complete its life cycle in maize to be 19-20 days at 25-300C, which was also the optimal temperature reported for the emergence of juveniles from the cysts.[17,18] However, Hutzel et al.,[19] found the optimum temperature for hatching to be 330C. Its spread and pathogenicity thus seem to be restricted by high temperature requirements (>300C).[10]

Moderately light soils have been found to be favorable for reproduction and the addition of clay to such soils has caused a decline in reproduction levels.[20] Better aeration and available oxygen in light soils seems to increase nematode multiplication.

Punctodera chalcoensis, also a cyst nematode, has only been reported from Mexico where it causes significant economic damage to maize and teosinte (*Euchlaena mexicana*), a close relative to maize and both are believed to have originated in Mexico.[21,22] Figure 1B shows the current world-wide distribution of the pest. Its host range is limited to maize and teosinte. *Punctodera chalcoensis*is found throughout Mexico, in temperate maize growing areas. It was considered to be present only in the vicinity of Chalco (the type locality); but its distribution has been reported in at least eight central Mexican states. It occurs from the Pacific Ocean to the Gulf of Mexico,[23,24] between 1500m and 3800m above sea level. Its distribution appears to be limited to Mexico.[23] It is suggested that *P. chalcoensis* is indigenous to Central Mexico and that it has co-evolved with maize.[21]

The environmental requirements of *P. chalcoensis* are unknown, although its distribution at high elevations (above 1500m in Mexico, and its absence in maize fields in warmer, subtropical regions suggests that it does not tolerate continuous, warm, humid conditions.[24] The nematode is most abundant in sandy soils.[21]

Figure 1A World distribution of *Heterodera zeae*.
Source: Plant wise knowledge bank.

Figure 1B World distribution of Punctodera chalcoensis.
Source: Plant wise knowledge bank.

The temperate conditions, which favour development of this nematode and its pathogenicity on maize, an important crop worldwide, may indicate potential for this nematode to become a widespread economic threat.[2]

Punctodera chalcoensis, a sedentary end parasitic nematode attacks the roots of the plant, damaging its nutrition and allowing other pathogens (e.g. fungi and viruses) access to the plant causing yield decline of about 90%.[25] The maize straw is so stunted that it is unusable.[26]

The pest has only one generation per year,[25–27] which coincides with the growing season of maize. Cysts left in the soil need a period of hibernation: diapause is broken in the spring, usually stimulated by the seasonal rains. Under laboratory conditions, Jeronimo[28] recorded a typical life cycle of about 30 days, although the life cycle can take up to 50days.[24]

The aim of the this study was to conduct a pest risk assessment (PRA) of *H. zeae*and *P. chalcoensis* on maize, which is an economically important crop grown in Belgium and the Netherlands, after it (H. zeae) had been recorded in other localities besides its centre of origin,[2,5,6,8,9] and in its current host range (*P. chalcoensis*) as primary pests of maize causing great yield reduction. The analysis follows the Pest Risk Assessment guideline of EPPO[29,30] and the use of CLIMEX, which is a dynamic simulation model for predicting the effects of climate on the distribution of plants and animals, by using climatic parameters inferred from an observed distribution. It is applied to different biological entities by selecting the values for the parameters that describes the organism's response to temperature, moisture and light.

The CLIMEX simulation model uses climatic information and knowledge about the biology and distribution of species in their original habitat, to provide a rapid, reliable assessment of the risks posed by the introduction of various organisms, and can be used to forecast their potential area of distribution. The climatic requirements of a species are inferred from its known geographical distribution (either in its native range or in another region where it has been established for a long time), relative abundance and seasonal phenology.

The CLIMEX model is a popular simulation software program[31,32] designed for conducting risk assessments for insect pests, weeds and diseases.[33–41] The program has the advantage, in comparison to other climate modeling softwares, that it includes a global meteorological database, which enables its Compare Locations module to be process-oriented. This therefore suggests that it is relatively resistant from the new climates problem which climate-matching and descriptive statistical models mighty encounter thus limiting their ability to perform global risk assessments.[42]

Even though *H. zeae* is not widely distributed in Europe, and *P. chalcoensis* has never been reported outside its original range of Mexico, they have the potential to extend their current range into new countries in the continent, through transportation of infected seeds and grains. This paper reports on an analysis undertaken to estimate the potential distribution and establishment of *H. zeae* and *P. chalcoensis* based on ecoclimatic suitability and the pest risk analysis guidelines so as to be able to predict occurrence of the study organisms in the study areas. The CLIMEX test was carried out at the Plant Protection Service in Wageningen in the Netherlands were the program is available.

Materials and methods

The computer simulation model CLIMEX version 2.0.[32] was used to determine the possible world geographic distribution of the corn cyst nematodes *H. zeae* and *P. chalcoensis* in general and in continental Europe in particular in relation to their currently known geographic distributions (Figure 1A) (Figure 1B), respectively). The CLIMEX software program uses a database of meteorological climate station data which are normally recorded as monthly means, and then interpolates this data to weekly values. The meteorological database supplied to the CLIMEX model is based on the database from the World Meteorological Organization.

Parameter fitting

The main parameter groups used in the case of *H. zeae* are: temperature index, moisture index, and heat stress (Table 1). Parameters that are not readily available are obtained from the parameter template, representative of different geographical distributions that are provided with the CLIMEX program.[32] The environmental requirements of *P. chalcoensis* are unknown therefore the above mentioned parameters did not apply.

Table 1 CLIMEX parameter values used to model ecoclimatic suitability for *H. zeae*

Parameter	Description	Value
Temperature		
DV0	Lower temperature threshold for growth	15°C
DV1	Lower optimum temperature	20°C
DV2	Upper optimum temperature	33°C
DV3	Upper temperature threshold for growth	36°C
Moisture		
SM0	Lower soil moisture threshold for growth	0.1
SM1	Lower optimum soil moisture	0.4
SM2	Upper optimum soil moisture	0.7
SM3	Upper soil moisture threshold for growth	1.5
Heat stress		
TTHS	Temperature threshold for heat stress	35°C
THHS	Heat stress accumulation rate	0.005 week–1
Dry stress		
SMDS	Soil moisture threshold for dry stress	0.2
HDS	Dry stress accumulation rate	0.05 week–1
PDD	Number of degree-days above DV0 necessary to complete one generation	757b degree-days

[a]Values without units are dimensionless indices.
[b]PDD value for *H. zeae*.

Temperature parameters

The temperature parameters for *H. zeae* were based on the reported findings of Wallace,[43] Srivasta,[18] Shahina et al.,[17] and Hutzel et al.[19] DV0 (lower temperature threshold for growth) was set to 15°C, because it is at below this temperature that germination, infection, and lesion production cannot occur. DV1 (lower optimum temperature for growth), DV2 (upper optimum temperature for growth), and DV3 (upper temperature threshold for growth) set at 20, 33 and 36°C, respectively. *H. zeae* has the highest reported temperature optimum for reproduction of any cyst nematode.[44]

Moisture parameters

The permanent wilting point of plants is generally near 10% soil moisture, and so the lower soil moisture threshold (SM0) of 0.1 reflects the need of *H. zeae* for more than the minimal amount of moisture to sustain its hosts' growth. The upper soil moisture threshold (SM3) allows *H. zeae* to grow during run-off conditions, and the lower and upper optimum thresholds (SM1and SM2) define a relatively broad, but wet, range of soil moisture conditions that should be optimal for the growth of the cyst nematode.

Heat stress parameter

He heat stress helps in containing the distribution of the cyst nematode *H. zeae* to the warm parts of Europe. Since heat stress cannot logically accumulate within the temperature range suitable for growth, heat stress was set to accumulate as temperatures increase above DV3, the upper threshold for growth (36°C). The rate accumulation parameter (THHS) was set to preclude the persistence of *H. zeae*in areas of Europe that are outside the known range of the cyst nematode.

Degree-days per generation (PDD)

The annual thermal accumulation (number of degree-days above DV0 [15°C]) necessary for *H. zeae* to complete a generation was adjusted to barely allow persistence at locations where the cyst nematode has been recorded in Europe. To determine the PDD values, CLIMEX fits a sine function to the minimum and maximum temperatures, and then calculates the integral of the function above DV0.[32] The PDD parameter is related to the length of the reproductive season, so it is ecologically important. *Heterodera zeae* was thus subjected to a CLIMEX analysis using a PDD value of 757.

In the case of a CLIMEX run for *P. chalcoensis*, since the environmental requirements are not known, the 'match climates' function, which allows for the comparison of the different climates of different locations on the globe, was used. Since very little information was available about the pest, the match climates function was used to provide a rough assessment of the risk of the pest establishing in the PRA areas. The match climate function in CLIMEX searches the long-term meteorological database for locations with climates similar to that of the target locations- namely Belgium and the Netherlands. Three weather stations were located near the type locality (Chalco), and Mexico City was chosen because it was comparable with the type locality. Mexico City is at 2308m (altitude), while the type locality Chalco is at 2300m. CLIMEX was then run with option 'match climate' at 0.5 levels and compared with Europe and the world.

Pest risk analysis

Heterodera zeae and *P. chalcoensis* do not occur in the PRA areas and have never been subjected to a PRA. The pest risk analysis of the two cyst nematodes on maize in Belgium and the Netherlands was conducted using the Pest Risk Assessment guideline of European and Mediterranean Plant Protection Organization (EPPO).[30] The pest risk assessment scheme of EPPO (PM5/3(5) used in this study, provides detailed instructions based on the experience of the European and Mediterranean Plant Protection Organization, for the following three sections of the pest risk analysis: the initiation phase, the pest risk assessment phase and the economic impact assessment and pest risk management phase. It provides a scheme for deciding whether a risk exists and for quantitative assessment of that risk, based on questions to which replies are given on a scale of 1-9. Guidelines on Pest Risk Analysis, i.e. a checklist of required information (PM 5/1-1) and a simple quick-PRA scheme (PM5/2-2) are also available. The latter one is only used when immediate action has to be taken on interception of a pest and therefore not used in this study. All three stages involved in a PRA were used for this study. These included:

i. The initiation stage which seeks to identify the reasons for the PRA and the pest(s) of concern in the PRA area.

ii. The Pest Risk Assessment Stage which seeks to identify and quantify the risk of a particular pest to a particular PRA area, in terms of the probability of its introduction and its potential economic impact.

iii. The Pest Risk Management Stage which is performed after a scientifically based risked assessment has been performed. The purpose of pest risk management is to decide whether the risk from the pest is such that phytosanitary measures are required to reduce the risk to an acceptable level and the measure(s) that should be applied.[45]

In addition to the afore-mentioned PRA stages, a checklist of information required for pest risk analysis was also used. The checklist contains all the information to be considered before deciding that a specific organism qualifies to be declared as quarantine pest. The list is intended to be used in conjunction with a stepwise decision-making scheme on pest risk assessment. Schemes of this type are being developed at different levels of complexity, by the European and Mediterranean Plant Protection Organization (EPPO) and the Food and Agricultural Organization (FAO).

Results and discussion

CLIMEX

Heterodera zeae was run with CLIMEX with a PDD value of 757 (Table 1), resulting in maps showing its potential distribution in Europe in general and in Belgium and The Netherlands in particular as well as a possible world distribution. The symbols on the maps represent the EI (Ecoclimatic Index), which integrates the Annual Growth Index with the Annual Stress. The EI can be seen as the climatological suitability of a location for a particular species. The value of EI lie between 0 and 100; the dots on the maps are in proportion to the EI values (1-100%, with 25% representing low suitability, 50% representing medium suitability and 75% representing high suitability.); 0% is represented as a cross.

Figure 2 shows a CLIMEX run with a mean PDD value of 757 for Europe. The prediction shows that *H. zeae* may become established only around the Mediterranean areas such as in Portugal, Spain, Southern France, Italy, Malta, Albania and Greece (where it has been reported before.[8,9] It would seem as if the pest cannot become established in the PRA areas - Belgium and the Netherlands - because these areas are too cool for its establishment being a tropical species with high temperature requirements. Figure 3 shows the CLIMEX prediction of *H. zeae* establishment in the USA at PDD 757. The prediction shows that the pest can become established mostly around the southern parts of the country and also around regions close to the Gulf of Mexico e.g. Texas, Arkansas, New Orleans, Georgia, Florida and also in areas such as Maryland and Virginia where it has already been introduced.[2,10,11]

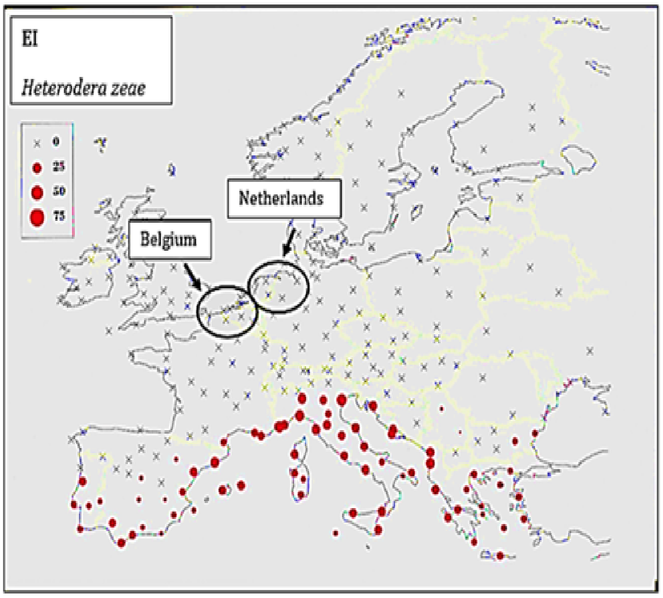

Figure 2 Predicted CLIMEX distribution of *Heterodera zeae* in Europe at PDD 757.

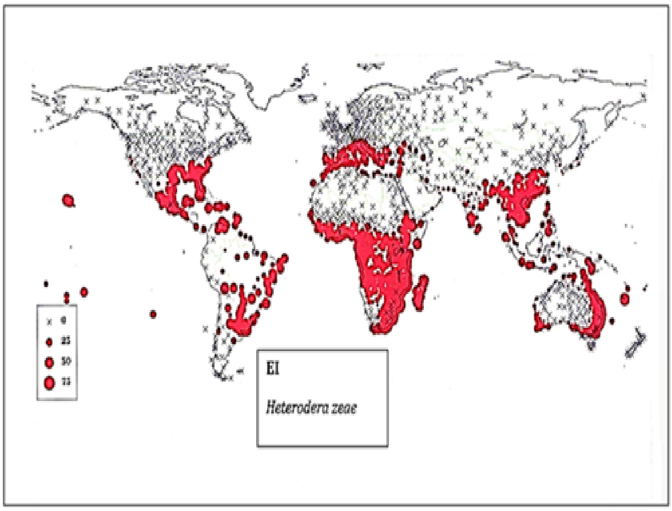

Figure 3 Predicted CLIMEX distribution of *Heterodera zeae* in the USA at PDD 757.

Figure 4 shows the prediction of CLIMEX at PDD 757 for the world. From this prediction, it can be seen that countries such as Argentina, Brazil, Uruguay, Paraguay and most regions of Central America are potential areas of establishment. In Africa, northern Africa including Tunisia, Libya, Morocco and Egypt (already present) and most of the countries below the latitude of 15° in the Northern hemisphere are facing potential danger. Countries such as India, China, Philippines, Vietnam and Australia are likely areas of establishment.

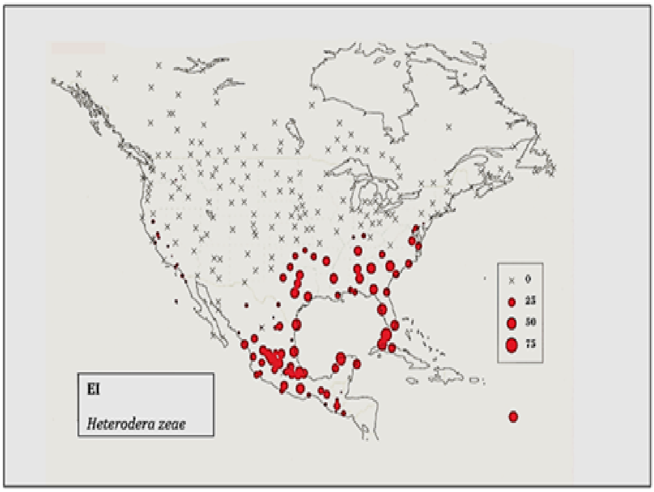

Figure 4 Predicted world CLIMEX distribution of *Heterodera zeae* at PDD 757.

To provide a more reliable prediction a PDD value of 757 was chosen and as a check, the PDD value correlated with countries where it has been introduced such as Egypt,[7] Portugal,[9] Greece[8] and the USA,[2,11] hence making the PDD value 757 even more reliable.

Figure 5 shows the potential distribution of *P. chalcoensis* in Europe based on CLIMEX prediction. Here, the "match climate" analysis was carried out by matching locations in Mexico close to the type locality Chalco and the whole of Europe. The matching analysis showed that there is a similarity between the climate of the maize belt in Mexico and that of a large part of the European continent, including Belgium and the Netherlands, with the exception of regions such as Russia. The match climate analysis also gives a rough assessment of the likely success of a species like *P. chalcoensis* in Europe.

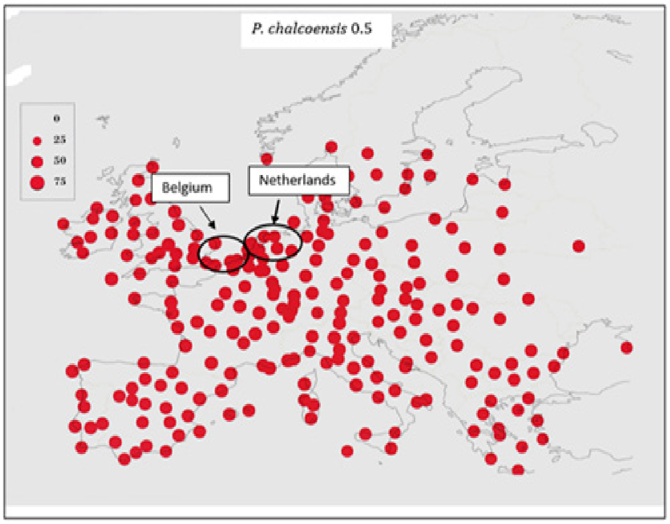

Figure 5 Predicted CLIMEX distribution of Punctodera zeae in Europe.

Because of the climatological similarity between the maize belt in Mexico and the PRA areas, there is a high probability of establishment of the pest if introduced in the PRA areas. The most likely factor involved here is temperature. Mexico and Chalco are located at high altitudes with cool temperatures comparable to those of much of the European continent, hence favorable conditions for establishment of the pest.

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Figure 6 shows the predicted distribution of the species through the world using the match climate function. The analysis shows that the possible distribution of this cyst nematodes is wider than of *H. zeae* with the exception of an area in central Africa. The entire Australian continent is in potential danger of establishment of this pest as well as the United States. Other countries where it is likely to be established include China, India, Pakistan and Korea in Asia, while in South America, it could get established in Argentina, Chile, Uruguay and Peru with the exception of Brazil, possibly because of the hot climate found in the region. The absence of establishment of the pest in Canada and Russia indicates that the pest cannot survive under extreme cold conditions.

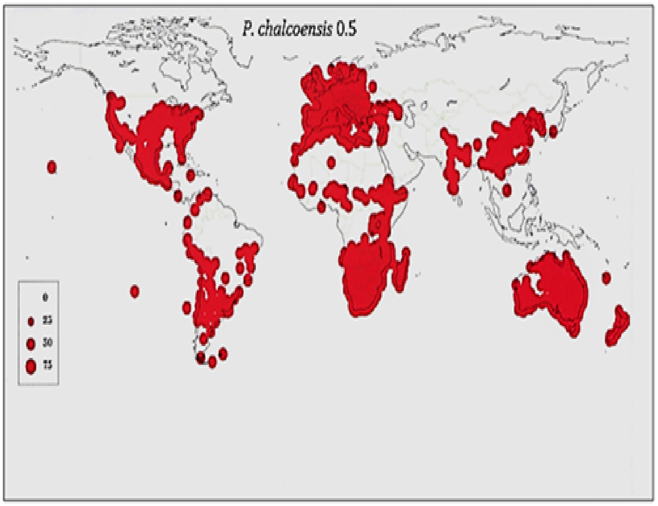

Figure 6 Predicted world CLIMEX distribution of Punctodera chalcoensis.

The hosts of the corn cysts nematode *H. zeae* include maize, barley, oat, rice, sorghum, wheat, several grasses and weeds,[10] but only maize and wheat are extensively grown in most parts of the PRA areas. The geographic distribution of the pest does not include ecoclimatic zones comparable with those of Belgium and the Netherlands. *Heterodera zeae* is a tropical species adapted to warmer areas and thus cannot be established in the PRA areas because of cooler climates present in these areas. However for southern Europe, the situation is different due to warmer climates in these regions. It is important to note that the pest can be introduced in the PRA areas through plant and plant materials contaminated with the pest moving through trade. Since the pest cannot be established in the PRA areas, it does not qualify as a quarantine pest for the PRA area, hence the pest risk management stage was excluded. However for the southern european countries and the other countries world-wide were the pest has the potential of establishing upon introduction, it can become a problem and therefore it is recommended to place this species on those countries' or regional alert list as a potential quarantine-organism.

The only host of the maize cyst nematode *P. chalcoensis* so far reported is maize and its wild relative teosinte. Mexico and Chalco (type locality of *P. chalcoensis*) has ecoclimatic zones comparable with those of Belgium and the Netherlands due to the fact that they are located at higher altitudes with low temperatures as comparable to those of the PRA areas.

Since maize is not imported from Mexico it is unlikely that infested plant material will be introduced in the PRA countries. It is however possible although unlikely that soil infested with this pest, meant for research purposes could be introduced. Although the chances of introduction of this pest into the PRA areas is very low, if introduced it can become established and might pose serious treats since maize is extensively grown in Belgium and the Netherlands.

Because of the pests' potential to cause great yield reduction, the pest is likely to have a significant effect on producers' profit. Once established, the pest will most likely be difficult to control because of their longevity and survival strategies like diapause and also high costs of chemicals which may not be very effective and which have been banned in the PRA areas. However, the presence of natural enemies may hopefully help in suppressing the pest population. The pest however, could present a risk because if introduced, although in small quantities, may become distributed to other areas through human assistance. Even though only rarely soil or plants with soil are imported into Europe from Mexico, it is important to place this pest on the list of quarantine organisms due to the potential harm it might cause upon introduction.

Conclusion

As every simulation program for phenomena in the natural world, CLIMEX has its limitations. The model only works with climatological data and climate-related species characteristics, not taking into consideration physical and biological factors such as soil type, dispersion capability and predators. The program works with long-term climatological data, and does not discriminate between favorable and unfavorable years. Taking the above mentioned facts into consideration, and also considering the Pest Risk Assessment, the following conclusions can be made about these studies.

Heterodera zeae, being a tropical species cannot become established in Belgium and the Netherlands because of the cool climate in these areas; however it is important to note the risk of establishment in the southern parts of Europe. It is therefore recommended to place this relatively dangerous cyst nematode on the mentioned alert list for quarantine-organisms as a potential quarantine organism, not only for the PRA study areas, but also on the alert list of all the other countries world-wide that are at potential risk upon introduction of the pest.

Punctodera chalcoensis can become established in both Belgium and the Netherlands as well as much of the European continent and could be placed on the European and Mediterranean Plant Protection Organization's alert list or quarantine list of organism, although the possibilities of its introduction in the PRA areas is very low. Because of its potential impact upon introduction, it is also recommended that the pest be placed on the alert list for quarantine-organisms of all the countries world-wide that are of potential risk upon introduction of the pest.

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Conflict of interest

The author declares no conflict of interest.

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