PEST RISK ANALYSIS FOR WESTERN CORN ROOTWORM (*DIABROTICA VIRGIFERA VIRGIFERA*)

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Summary

1. Western corn rootworm (WCR), one of the most important maize pests in North America, and increasingly important in central Europe, has been found in the south east of England. The pathway by which WCR arrived in the UK has not been identified although there appears to be a link with international air transport.

2. WCR is primarily a pest of continuous maize. Approximately 120,000 ha of maize are grown each year for silage, of which an estimated 20% is continuous. A much smaller area of maize is also grown for grain production, sweetcorn, and as game cover. A small proportion of larvae can develop to adults when fed on cereals such as wheat and barley but more research is required to determine how fecund (fertile) females developing from these alternative hosts would be.

3. As the UK climate warms conditions are becoming increasingly suitable for WCR to establish in a larger portion of the UK maize crop. By 2050, all of the UK maize crop is likely to be vulnerable.

4. Although WCR can establish in southern England under current climatic conditions, population densities are likely to remain low unless the area of continuous maize increases from its current level.

5. Experiences in central Europe, where the summers are significantly warmer and WCR has been present for over ten years, suggest that significant economic impacts, due to larvae feeding on roots causing yield losses and crop lodging, only occur after several years of continuous maize cropping. Crop rotation is the most effective means of controlling WCR and in regions where WCR has caused significant damage some European farmers are now switching to growing maize in rotation.

6. A range of alternative management options for control or eradication of WCR have been used in areas where the pest occurs. Of the three insecticides approved for use in the UK only chlorpyrifos (an organophosphate) has been shown to be effective against WCR. However, the use of this chemical is under review in the UK and its future availability cannot be assured.

January 2007

PEST RISK ANALYSIS FOR *DIABROTICA VIRGIFERA VIRGIFERA*

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STAGE 1: PRA INITIATION

1. Name of pest (Genus, species, subspecies, Authority, Order, Family, Common Name)

Diabrotica virgifera virgifera Le Conte Coleoptera Chrysomelidae western corn rootworm

The common name refers to the larval life stage of the species that feeds on maize (corn) roots.

Synonyms: *Diabrotica virgifera* LeConte
Diabrotica filicornis Horn
Diabrotica virgifera var. *filicornis* Gillette

The species *Diabrotica virgifera* was split into two subspecies, *Diabrotica virgifera virgifera* (the western corn rootworm) and *D. virgifera zeae* (the Mexican corn rootworm), by Krysan *et al*. (1980). Justification for distinguishing the subspecies is based on morphological differences, geographical distribution, mating choice, competitiveness and responses to pheromones.

2. What is the reason for the PRA?

The North American pest *Diabrotica virgifera virgifera,* also known as the western corn rootworm (WCR), was first observed in Europe in the vicinity of Surcin airport, near Belgrade, (Yugoslavia) on a small maize plot (0.5 ha) in July 1992. It is thought that it may have been introduced in 1990 by military air transport from North America (EPPO, 1996). The first UK PRA was conducted in 1994 to confirm the need for EC/EPPO listing. Since then, WCR has been spreading within both Eastern Europe and the EU. It was first found within the EU in Italy in 1998, see 4.].

With the dramatic increase in the area of maize grown in the UK since the late 1980s (see Annex 1) and the detection of the pest around Paris in 2002 (Reynaud, 2002), the risk of the organism spreading into the UK was reassessed in January 2003 (MacLeod *et al*., 2003). A key requirement was to determine the extent to which a trapping programme needed to be carried out. Following findings of the pest on traps near Heathrow and Gatwick airports in August-September 2003, a further update to the PRA was carried out.

This document updates the previous PRA to include scientific information published between September 2003 and December 2006 and has been prepared as part of a public consultation exercise.

3. What is the PRA area?

This PRA considers only the UK since the pest is already established in continental Europe. The analysis focuses on England and Wales.

STAGE 2: PEST RISK ASSESSMENT

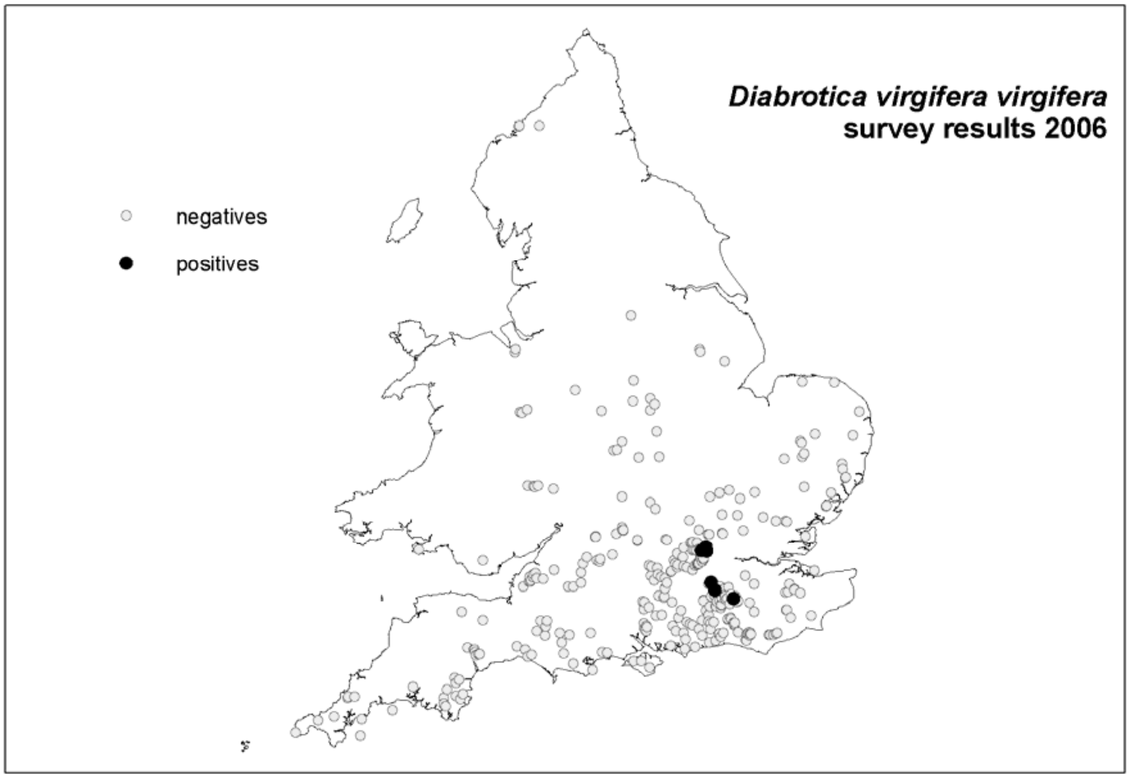
4. a) Does the pest occur in the PRA area, or b) Does it arrive regularly as a natural migrant?

a) Yes, WCR is present in the UK with a limited distribution. It occurs in a localised area of the south east of England.

b) No. Although WCR can fly up to 24 km in a single flight (Coats *et al*., 1986) the English Channel is approximately 34km wide at its narrowest point and there are no colonies of WCR on the northern coast of France. WCR is therefore not presumed to be capable of arriving as a natural migrant.

WCR was first found in the UK at two sites near Heathrow Airport in August 2003, as anticipated by an earlier PRA (MacLeod *et al*., 2003). In September 2003 it was also found near Gatwick Airport. Following the first confirmation of WCR in England monitoring has been undertaken annually. Pheromone traps and lures are used in demarcated zones surrounding the outbreak areas and more widely as a national survey in maize-growing areas throughout the UK (devolved administrations and crown dependencies). In 2005, trapping was intensified within an extended 20km buffer zone around known outbreaks to include 100 additional monitoring sites. Figure 1 shows the results of the 2006 survey in England & Wales.

Figure 1: Locations of traps used in the 2006 survey of England & Wales with finds of adult WCR shown.



5. Is there any other reason to suspect that the pest is already established in the PRA area?

WCR has been confirmed in south east England each year since 2003. The large numbers of beetles (over 50) caught in one field near Heathrow in 2003, suggest WCR may have been present in the area for at least one year before it was first found. On the basis of the annual surveys since 2003, in which approximately 2,000 pheromone traps have been used per year at approximately 500 separate locations, we are confident that the beetle remains localised to a few foci in south east England (Figure 1).

6. What is the pest's status in the Plant Health Directive (Council Directive 2000/29/EC[1])?

Diabrotica virgifera is listed in Annex IAI of the EC Directive 2000/29/EC. Organisms listed on Annex IAI are harmful organisms whose introduction into, and spread within all Member States shall be banned. However, WCR has established in parts of the EU (see 11.) and should now logically be in Annex IAII (harmful organisms known to occur in the community and relevant for the entire community). Note that the Directive does not distinguish between the two subspecies of *D. virgifera,* i.e. between *D. virgifera virgifera* (WCR) and *D. virgifera zeae* (Mexican corn rootworm). This distinction should be recognised so that *D. virgifera zeae* becomes listed in Annex IAI and WCR is listed within Annex IAII.

EC Decision 2003/766/EC[2], which prescribes an annual survey and phytosanitary treatments, and 2006/564/EC[3], which prescribes measures around airports also apply to WCR.

7. What is the quarantine status of the pest in the lists of the European and Mediterranean Plant Protection Organisation (EPPO)? (www.eppo.org)

EPPO List:	A1 regulated pest list		A2 regulated pest list	X	Action list		Alert list	

WCR is listed as an EPPO A2 pest. Organisms included in the A2 list are pests which are regulated by EPPO countries on EPPO's recommendation and which are locally present in the EPPO region.

According to EPPO PQR (2005), Chile is the only other country, apart from those in EPPO, to list *Diabrotica virgifera* as a quarantine pest.

8. What are the pests' host plants?

Maize / corn (*Zea mays*) is the primary host for WCR with adults and larvae feeding on different plant parts. Adults feed on flowering maize pollen, silks,

[1] http://europa.eu.int/eur-lex/en/consleg/pdf/2000/en_2000L0029_do_001.pdf
[2] http://eur-lex.europa.eu/LexUriServ/site/en/oj/2003/l_275/l_27520031025en00490050.pdf
[3] http://eur-lex.europa.eu/LexUriServ/site/en/oj/2006/l_225/l_22520060817en00280029.pdf

leaves and young developing kernels. In North America adults also feed on a large number of other plants found around and within maize fields that flower in the summer and early autumn (Metcalf & Metcalf, 1993). Similarly, European studies indicate that adults feed on pollen from a wide range of alternate hosts including Asteraceae, Chenopodiaceae, Cucurbitaceae, Fabaceae and Solanaceae (Cheek, 2003; Moeser & Vidal, 2003; Moeser & Vidal, 2005). However, such studies have not confirmed the food plants as true hosts since they did not show that larvae survived to adulthood and successfully reproduced.

Annex 2 lists North American hosts and potential European hosts.

Larvae cannot discriminate between the roots of plant species (Krysan & Miller, 1986) and will feed on roots closest to where they hatch. Larvae locate roots by being attracted to carbon dioxide, escaping from plant roots during respiration (Bernklau *et al*., 2004; Fischer *et al*., 2006). Hibberd *et al*., (2003) suggest WCR larvae can move up to nearly 50 cm so they should be able to find some plant roots under most circumstances. However, larvae have a limited host range and are only able to mature to fecund adults if they feed on the roots of a limited number of grass species (see Annex 2). Moeser & Vidal (2003; 2005) studied European populations of WCR larvae feeding on European grasses and found that although all grasses tested were eaten, there were significant differences between the grasses with respect to larval weight gain. Grasses providing the greatest weight gain are presumed to be more favoured alternate hosts. Adults developed from larvae fed on *Setaria verticilaria*, *S. glauca* and *Panicum miliaceum*. All three of these grasses occur in the UK. However, Moeser & Vidal (2003) did not measure adult fecundity. Thus, although it was shown that individuals could develop on European monocotyledons other than maize, the number of eggs laid by adults was not assessed and is very likely to be much lower than the number of eggs laid by adults that develop on maize. Moeser & Vidal (2003) confirmed that European populations of WCR larvae were able to develop when fed on winter wheat (cv. Bussard) but again did not measure fecundity. In a separate trial these authors noted that plant species with a high nitrogen content are less suitable for WCR development (Moeser & Vidal, 2005).

In trials in Germany by Breitenbach *et al*., (2005) only eight WCR larvae survived from an initial population of 75 larvae that were fed on wheat, i.e. approximately 10% of larvae survived. This is much lower than the 33% (43 surviving larvae from an initial population of 130) fed on maize. Wheat (*Triticum aestivum*) and spelt (*T. spelta*) are alternate hosts on which larvae can develop although many fewer adults emerge and those females that do develop are likely to be much less fecund (lay less eggs) (Branson & Ortman, 1970). Gloyna & Theime (2006) tested WCR development on barley, oat, rye, spelt, triticale and wheat. Adults developed from larvae fed on each host except oats. Further research to investigate female fecundity amongst those developing from hosts other than maize is required to determine the consequences of cereals being potential alternate hosts.

Successful development will depend on sufficient root material being present within the range of larval movement. The extent to which WCR population development will be as successful on alternate hosts, as on maize, will also be determined by the selection pressure imposed, e.g. by crop rotation. Using wheat or other monocotyledonous crops in maize rotations may select for enhanced WCR development on alternate hosts. In such circumstances eradication through use of crop rotation using Poaceae seems unlikely (Moeser & Vidal, 2003) although rotation would still be a major part of WCR pest management.

In some regions of North America, WCR has adapted to the rotation of maize with soyabean. Such adaptation occurred over a 20-year period due to evolutionary selection pressure (Levine *et al*., 2002). In the UK, if maize were only to be rotated with a single other crop e.g. wheat, then over time WCR may adapt to overcome rotation.

9. What hosts are of economic and/or environmental importance in the PRA area?

Maize grown for cattle feed (forage maize) accounts for around 97% of the total area of maize grown to be harvested (i.e. excluding maize grown for game cover). With game maize included, forage maize represents around 90% of all maize. Grain maize for small animal feed, e.g. pigeons and corn fed chicken represents approximately 2% of the total maize area, and the remainder, approximately 1% is grown for sweetcorn (Nix, 2006).

As suggested above, maize can be a significant component of game cover. There are conflicting estimates regarding the area of maize used for game cover. The Game Conservancy estimates approximately 2,100 ha is grown annually whilst the Maize Growers' Association (MGA) states that maize for game cover is grown much more widely. Sales of maize seed used for game cover suggests around 10,000ha is grown annually. Table 1 assumes 10,000ha is used in game cover.

Table 1: The area and value of maize grown according to its use. (Data from various sources)

Intended use	Gross margin [(a)] (£/ha)	Area grown ('000) (ha)	Value (£'000)	% of total area
Forage maize	475[b]	120[c]	57,000	89.6
Game cover	900	10[d]	9,000	7.5
Maize grain (e.g. pigeon food)	410	3[e]	1,230	2.2
Sweetcorn (human consumption)	975	1[f]	975	0.7
		134	68,205	100.0

(a) Based on ADAS (2004)
(b) Prices can range from £250-£800/ha according to potential yield and local market conditions, although £425-£525 would be more typical (Nix, 2006). The mid-point of £475 is used in the analysis.

(c) based on Annex 1
(d) The game cover area varies according to sources. See text for details.
(e) Nix (2006) estimates perhaps 3,000 ha of grain maize is grown. This has increased from the 1,500 ha estimated by Nix (2002)
(f) UK DEFRA stats http://www.defra.gov.uk/esg/work_htm/notices/janveg.pdf (area was actually recorded as 1,170 ha but the figure has been rounded down in Table 1)

There is no reason to believe that these areas will change significantly in the future although the Single Farm Payment Scheme and Mid-Term Review of the CAP may have an effect on the amount of animal feed maize (ADAS, 2004).

ADAS (2004) provided a breakdown of forage maize production across the regions of England and Wales and is reproduced as Table 2. The figures show that the key maize areas are in the South East, East of England, South West and West Midlands. The last column indicates the importance of maize in cattle rations, e.g. the South East has 18% of maize area but only 7.6% of cattle, compared to the East Midlands which has 6.1% of the maize and 7.7% of the cattle. Thus, more maize is grown per cow in the South East than in the East Midlands.

Table 2: Maize area and proportion of cattle in the regions of England and Wales

Region of England & Wales	Maize area (ha)	% of maize	Total cattle ('000)	% of cattle	Ratio % maize: % cattle
South East	19,236	18.0	595	7.6	2.37
East of England	6,429	6.0	266	3.4	1.77
South West	45,515	42.6	2,081	26.5	1.60
West Midlands	13,500	12.6	893	11.4	1.11
East Midlands	6,516	6.1	606	7.7	0.79
North West	7,465	7.0	1,127	14.4	0.49
Wales	6,119	5.7	1,291	16.5	0.35
Yorks & Humber	1,949	1.8	643	8.2	0.22
North East	207	0.2	337	4.3	0.05
TOTAL	106,936	100.0	7,839	100.0	

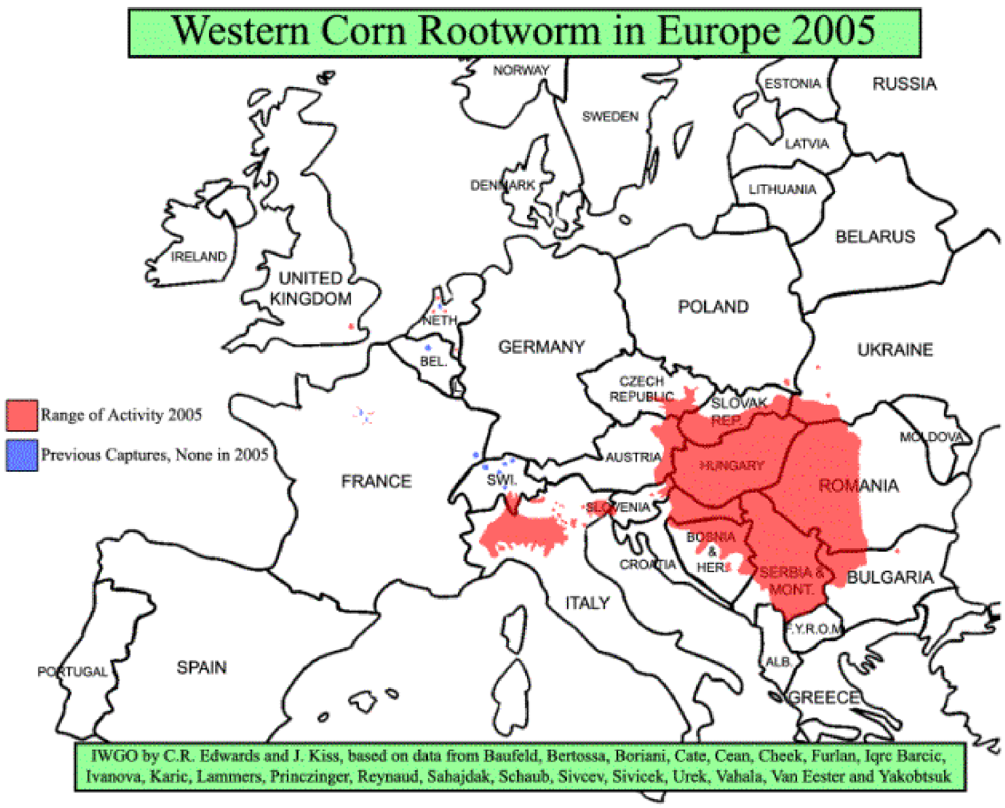
Source: June Census 1999 / ADAS 2004

10. If the pest needs a vector, is it present in the PRA area?
No vector is required. This is a free-living organism.

11. What is the pest's present geographical distribution?
WCR is present in the USA and Europe. WCR is a North American beetle whose original distribution appears to have been within the foothills to the east of the Rocky Mountains (Colorado, USA). It was first recorded as a pest of maize in 1909 in Colorado. It then spread slowly eastwards to Nebraska (1929), Kansas (1945), Missouri (1960) and Illinois (1964). Continuously grown maize, i.e. without rotation, has largely been responsible for the spread of WCR in North America (Metcalf & Metcalf, 1993). It is now found from Ontario to North Carolina and is present throughout the central and eastern USA and into Canada (Ontario and Quebec (Meloche *et al*., 2001)). The rate of spread of WCR in the USA was between 44 and 125 km/year (Onstad *et al*., 2003).

WCR was first found in Europe in Yugoslavia in 1992 (see 2.). It was first detected in the EU in Italy, at the end of July 1998 close to Venezia airport (Marco Polo di Tessera) (EPPO, 1998a). It has since spread within the EPPO region and the EU. Figure 2 shows the European distribution of WCR as at November 2005. Annex 10 shows the annual spread of WCR in Europe between 1992 and 2004.

Figure 2: Distribution of western corn rootworm in Europe (as at November 2005).[4]

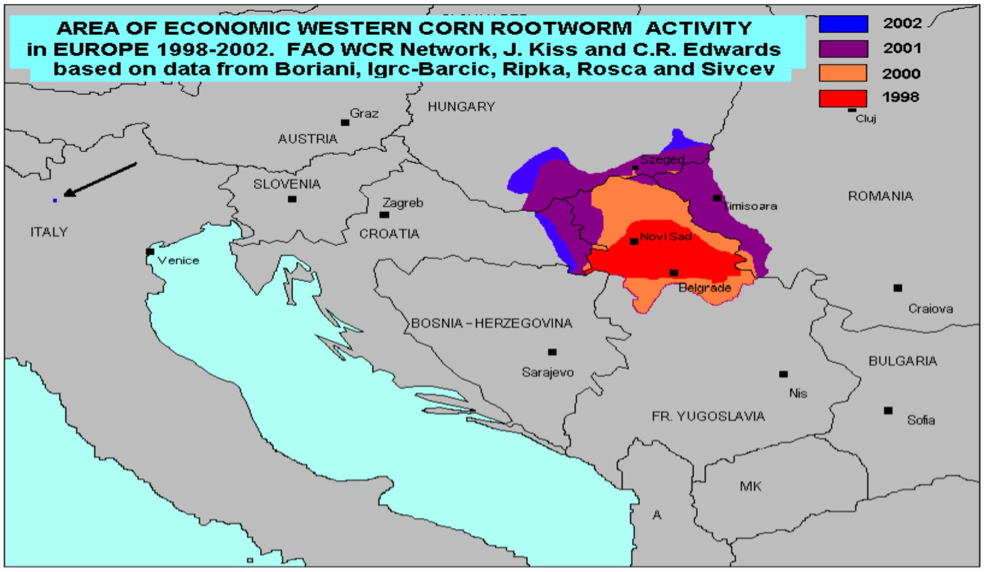


In Europe, WCR was first detected in Yugoslavia in 1992 and has since spread. It is now present in Croatia (first found in 1995), Hungary (1995), Bosnia & Herzegovina, Romania (1996) Bulgaria, Montenegro, Italy (1998), Slovakia, Switzerland (2000), Austria, Czech Republic, France (2002), where an intensive eradication campaign has been mounted around three airports near Paris (EPPO, 2003), Ukraine (2002), Belgium, Netherlands, Slovenia, UK (2003) and Poland (2005).

[4] Annex 10 shows the annual spread of WCR in Europe between 1992 and 2004.

During 2003 WCR was detected around a number of international airports, for example in France near the Swiss border and Basel airport, in the Netherlands near Schiphol airport, in Belgium near Zaventem (Brussels) airport, in Slovenia and in the UK near Heathrow and Gatwick airports.

Figure 3: Regions where WCR causes economic damage in Europe (as at Nov. 2002).



12. How likely is the pest to enter the PRA area[5]?

Very Unlikely		Unlikely		Moderate Likelihood		Likely		Very Likely	X

WCR was first found in the UK at two sites near Heathrow Airport in August 2003, as anticipated by an earlier PRA (Macleod *et al*., 2003). In September 2003 it was found near Gatwick Airport.

The first finding of WCR in most European countries has been associated with airports, e.g. the first European finding was in July 1992 near Surcin airport, close to Belgrade (Yugoslavia) (EPPO, 1996). In Italy, WCR was first found in 1998 near the Marco Polo International Airport of Venice. Outbreaks have since occurred near Milan airport (Malpensa) (EPPO, 2001) and near Aviano military airport in Friuli-Venezia-Giulia (Italy) during 2002 (EPPO, 2003). In Switzerland, it was first found near Lugano/Agno airport in Ticino (EPPO, 2001). In France, WCR has been found near the three Paris airports (Reynaud, 2002). It was first trapped in August 2002 near Le Bourget and Roissy airports (region Ile de France). WCR has since also been trapped near Orly airport, in the same region

[5] Pest entry includes an assessment of the likelihood of transfer to a suitable host (ISPM No. 11, FAO, Rome)

(EPPO 2002b). In July 2003, it was found in Blotzheim (France) near the German and Swiss border and close to Basel airport (Switzerland). In the Netherlands, two adult WCR were found on a trap in a maize field near Schiphol airport in August 2003. Adult WCR were found at Zaventem Airport, Brussels in September 2003.

There is no agreed hypothesis to explain why the introduction of WCR is associated with airports. Throughout Europe there has been a tendency to trap more intensively near airports and there may simply be cause and effect. However, with so many reports of findings near airports, as well as the UK finding near Heathrow and Gatwick, and latterly the findings near Zaventem Airport, Brussels, despite increasing trapping elsewhere the association does appear to be real.

The most noticeable feature of airports and aeroplanes at night is that they are brightly lit and some night-flying beetles are attracted to lights. However, although there is some disagreement in the scientific literature, the main flight periods of WCR are said to be early morning and late afternoon, which is a flight pattern common to many insects. Some night flying beetles are attracted to the very bright lights, e.g. those used for loading aircraft at night. However, WCR does not fly at night (Isard *et al*., 2000). WCR adults are most likely to fly either in the morning (7.00-11.00) or in the early evening before sunset (Naranjo, 1990; Isard *et al*., 2000). In Europe, Hungarian studies confirmed daily peaks of flight activity between 7:00 and 10:00 and again between 17:00 and 19:00 (work by Wennemann & Hummel, noted by Cheek, 2003). However, in laboratory experiments, Coats *et al*., (1986) reported greatest flight activity between 18:00 and 24:00 with no sustained, migratory, flight during daylight hours. One expert in the USA has suggested there is an attraction to light with a yellow tinge. With airports being on the edge of towns and close to maize with high infestations, it is perhaps inevitable that some will enter aeroplane cabins and baggage holds.

Speculation that adult WCR are attracted to airports lights, or kerosene fuel vapour, and are subsequently carried and spread via aircraft, was quashed following publication of results of trials in Hungary that failed to show that such lights or fuel acted as an attractant to WCR (Baufeld *et al*., 2006).

The significance of even one beetle moving in aircraft is considerable, as a female is likely to have already mated and be capable of laying fertile eggs after arriving in a new area. It is known that the females are the most important dispersive life stage of the insect; flying longer distances than males (Naranjo, 1990).

WCR is very mobile and strongly dispersive (Coats *et al*., 1986). On two separate recent occasions entomologists have identified WCR in aeroplane passenger cabins. An alternative possibility is that they are ‘caught’ by the plane's undercarriage as they take off and fly above maize fields where the pests may be abundant as they disperse; but there is no evidence for this supposition.

Based on genetic variations between different populations, Miller *et al.* (2005) and Guillemaud & Miller (2006) show that three out of five analyzed western European WCR outbreaks did not originate from the WCR infested region of Central Europe, but from the USA. Moreover, the introductions to western Europe were independent from each other and from the initial European introduction. Thus they concluded that WCR has been introduced from the USA on at least three other occassions since it was introduced to Serbia.

However, this does not explain why a pest that has been so abundant in North America for so many years has no previous history of entering Europe, presumably on aircraft, from North America.

There is no evidence of WCR being associated with imported grain or corn cobs and whole maize plants are not traded. CSL has no records of WCR ever arriving with an import, and is not aware of any records of movement with traded plants or produce. So, the likelihood would seem to be that it is carried in the aeroplane itself, and not with goods.

13. How likely is the pest to establish outdoors in the PRA area?

Very Unlikely		Unlikely		Moderate likelihood		Likely		very Likely	X

The extent to which the UK climate is suitable for establishment has been considered in detail in Annex 3. The conclusions are repeated here:

Li *et al*., (2006) predicted the potential global distribution of WCR and predicted the northern limit to be 55^{o}N. Thus under current climate conditions, WCR appears to be at the edge of its range in the UK. However, predictions of climatic suitability for WCR are not easy to make because all stages, except the adult, live in the soil (Annex 8) and WCR's environmental responses which have been reported in the literature are difficult to extrapolate to UK conditions primarily because we have no comprehensive soil temperature profiles for the maize crop in the UK. Nevertheless, comparisons of air and soil temperatures at different depths from locations south of London indicate that,
(a) WCR could complete its life cycle in most if not all of the last thirty years, and
(b) the warmer summer temperatures in the most recent years have greatly increased the likelihood of this occurring. Outside southern England, the likelihood of WCR completing its life cycle rapidly diminishes.

WCR's establishment potential is also likely to be influenced by the following factors:

- Its principal food plant, maize, is grown widely. The highest density of maize is in south and south-west England where it is mainly used as cattle feed.

Although wild plants are not likely to be significant in the dispersal or maintenance of populations, wheat, a poor secondary host, is very widely grown. In Europe WCR has been shown to be very adaptable, e.g. adding several European species to the range of plants on which adults feed (Moeser & Vidal, 2003; Breitenbach *et al*., 2005), and it is possible that other plants may also prove suitable for development in the UK.

- Although natural competition and predation are not likely to affect establishment, crop rotation is the most important factor affecting the population dynamics of WCR. However, on its own, rotation is unlikely to prevent establishment since the life cycle can still be completed on other hosts, although by fewer individuals. Adults can disperse widely (perhaps up to 100 km per year (Coats *et al*., 1986; Baufeld & Enzian, 2001), they are highly fecund (Elliot *et al*., 1990) and a small proportion of eggs (<1%) may delay hatching for one year (Levine & Oloumi-Sadeghi, 1991).
- Throughout its current range WCR shows considerable variability with selection pressures leading to insecticide resistance, for example, cyclodiene resistance developed in the US in the 1960s (Metcalf, 1973; 1976) and more recently methyl parathion resistance developed in Nebraska, with evidence of tolerance to carbaryl as well (Meinke *et al*., 2001; Siegfried *et al*., 2001).
- Even low populations of WCR are likely to become established because males are attracted to female hormones.
- A key uncertainty is the probability that another cool summer, similar to 1996, will occur, and limit the area suitable for WCR survival, under conditions of climate warming.

Baker *et al*. (2003) used CLIMEX to identify the parameter that is critical to defining the northward limit of WCR distribution in North America, i.e. an accumulated temperature threshold, and then applied this to the UK at improved spatial and temporal resolutions under current and future climates. It was noted that considerable uncertainty remains as to the choice of the minimum threshold of 11°C and the limit to the annual accumulated temperature being set at 670. It was found that there is considerable annual variation in the area available for establishment, e.g. in the cool summer of 1996, less than 0.1% of the maize area in England accumulated the temperatures required for the successful development of a generation. In contrast, during the very hot summer of 1995, 97.8% of the maize area in England accumulated the temperatures required for the successful development of a generation. By 2050 under global warming the temperatures of 1995 are likely to be representative of the mean rather than an exception (Hulme *et al.,* 2002).

Annex 11 shows how the average area of maize suitable for WCR development is expected to grow, and how an estimate of the area suitable for WCR development was calculated taking climate change predictions into account.

14. How likely is the pest to establish in protected environments in the PRA area?

Very Unlikely	Unlikely	Moderate Likelihood	Likely	Very Likely
X				

WCR is not recorded as a pest in protected cultivation. The crop at risk is maize, which is not grown in protected environments.

15. How quickly could the pest spread within the PRA area?

Very Slowly	Slowly	Moderate pace	Quickly	Very Quickly
	X			

Although WCR has been present in England for at least four years, surveys have shown that it has not spread far from sites where it was first found in 2003. Clearly WCR has spread dramatically in Europe but, based on results of annual WCR surveys, including extensive trapping in the vicinity of previous finds, such spread has not occurred in England. Equally spread has not been reported since the initial finds of WCR at Parisian airports.

Short distance movement occurs when adults walk or fly at low elevations (<5 m above ground level) within and between fields. Such types of movement are responsible for low rates of spread. Greater spread occurs when newly mated females disperse aerially above 10 m. In laboratory trials, females were found to fly for up to 4 hours at a time, travelling up to 24 km in a single flight (Coats *et al*., 1986). In such experiments it was found that the mean distance covered per day was 35 km. Mated females were found to undertake sustained flights for up to 9 days after eclosion (adult emergence). Aerial dispersal can also be assisted by travelling in prevailing winds (Johnson, 1969). Grant & Seevers (1989) linked long distance movement and dispersal of WCR with the movement of cold weather fronts. The original spread of WCR in the USA occurred at a rate of between 44 and 125 km/year. Increased landscape diversity, with fields of maize and other crops, is likely to slow the rate of spread, e.g. spread was slowed to 33km/year in diverse landscapes compared to between 44 and 125 km/year in more homogenous landscapes (Onstad *et al*., 2003).

Annex 10 shows the spatial and temporal spread of WCR in Europe from 1992 to 2004. WCR has spread from the original site of infection at different rates. Spread northwards has been fastest at a mean of around 40 km per year, although spread has been as low as 4 km (in 1998) and as high as 88 km (1995) in this direction (Annex 4). Spread eastwards has been slower, averaging 21 km per year, whilst westward spread averaged 27 km per year. Spread eastwards and westwards is limited by mountains, i.e. the Carpathian mountains (in Romania & Ukraine) to the east, the Dinaric Alps (in Bosnia & Hercegovina) to the south and west, and by the Balkan Mountains (in Bulgaria) to the south east. It is assumed that maize is not grown in these mountainous regions.

In the Czech Republic, WCR has spread approximately 80 km in three years (an average of around 27km /year) (Brezikova & Zaruba, 2006). In Slovenia WCR spread 40km in 2005 (Modic *et al*., 2006).

Baufeld (2003) modelled the spread of WCR in parts of continental Europe where it has not yet reached. He used two spread rates, 20km/year with containment measures in place and 80km/year without containment measures. If the maize area was less than 50% of the total crop area, these rates were reduced in proportion to the area of maize grown as a percentage of all other crops in each region. Thus spread was predicted to be fastest where maize planting dominated the arable area and was slowest where maize accounted for only a small area amongst other crops.

The rate of spread within the UK will depend on flight activity and the factors affecting long distance dispersal. Temperature has a significant influence on flight activity (initiation and duration). Witkowski *et al*. (1975) showed that WCR flight activity peaked within the range 22-27°C, while Naranjo (1991) showed peak activity at slightly cooler temperatures around 20-25°C. Adults can fly at 15°C although between 15 and 20°C it is the males that are more active. Temperatures in the UK may limit the initiation and duration of flights and the low density of maize (i.e. scattered fields) could slow the rate of spread, as suggested by the work of Baufeld (2003).

The rate of WCR spread in the UK will very much depend on the proportion of the maize area that is continuously in maize. A Maize Growers' Association (MGA) survey conducted in around 1998, found that approximately 20% of maize was continuous with around 80% grown in rotation. The ratio is probably much the same today (S. Draper, pers. comm.). Continuous cropping of maize in North America has largely been responsible for its spread northwards in the USA and Canada. The growing of continuous maize has also been a factor in facilitating the growth in population density and spread of WCR in Europe.

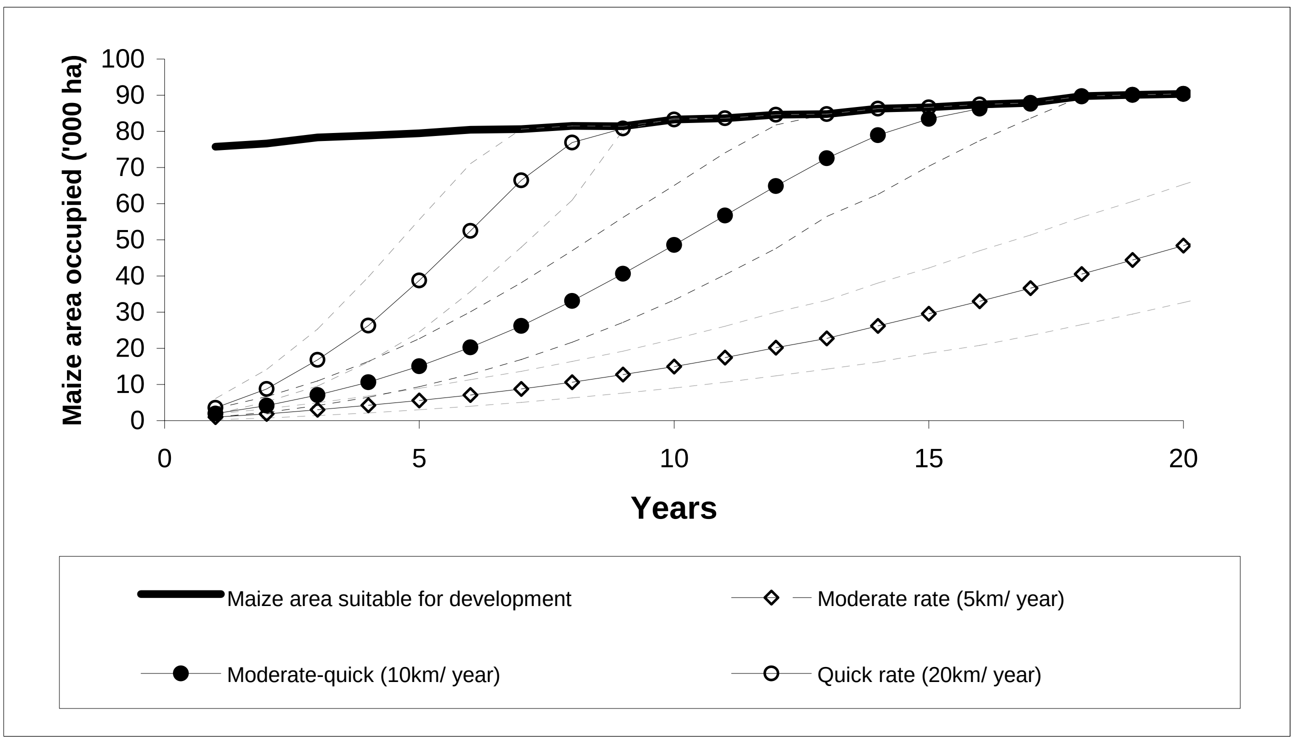
As noted in 13. above, climate is critical in determining the area within the UK that WCR can occupy. Using historic summer temperature data for a cool year (1996), a typical year (1997) and a hot year (1995), the area of maize where temperatures accumulated sufficiently to allow WCR to complete a generation was calculated. These areas were then used to provide sample distributions of the range of maize areas that could be occupied each year according to climatic conditions. Later analysis, confirmed that 1995 was a hot year, 1996 was a cool year, and 1997 a more typical year (see Annex 12).

To take account of the time taken to spread, three scenarios with three different distributions of rates of spread were considered.
Scenario 1: a moderate rate of spread was expected, ranging from a minimum of 0 km/ year; typically 5 km/ year and with a maximum of 15 km/ year.

Scenario 2: a moderately quick rate of spread was expected to have a minimum of 5 km/ year; typically 10 km/ year and a maximum of 25 km/ year.
Scenario 3: the most rapid spread was expected to range from 10 km/ year; typically 20 km/ year and with a maximum of 40 km/ year. A stochastic Monte Carlo simulation model combining the area that could be occupied each year according to climatic constraints and taking into account the rate of spread showed that, with quick spread (scenario 3), on average, WCR would be able to occupy just over 82,000 ha of maize each year in approximately 8 years time (for further details see Annex 5).

Figure 4 shows the mean area of maize infested by WCR each year as it is predicted to spread from the current outbreaks near Heathrow and Gatwick over the next 20 years, taking variable climate and the three different rates of spread scenarios into account. It is assumed that the area of maize grown each year does not significantly change (See Annex 5 for further details).

Figure 4: The mean area of English maize infested as WCR spreads at either 1) a moderate rate (5km /year), 2) a moderate-quick rate (10km /year), or 3) a quick rate (20km/ year) ('000ha).



16. What is the pest's potential to cause economic and/or environmental damage in the PRA area?

very Small	X	Small		Medium		Large		very Large	

In the immediate future, the potential for economic damage by WCR is very small since it takes time for populations to build up in fields of continuous maize before economic damage occurs. In the medium term the potential for economic damage is small since most maize is grown in rotation, which will inhibit the build up of populations to damaging levels. However, in the longer term, pest populations could be more damaging as the climate changes and WCR spreads to areas where it is difficult to rotate maize.

In North America WCR is a serious pest of continuous maize (Oerke *et al*., 1994). Larval root feeding is the primary source of damage, reducing nutrient uptake and growth (Gavloski *et al*., 1992). Root damage also weakens plants and makes them more susceptible to lodging in wet or windy conditions. This can inhibit or even prevent crop harvesting. In continuous maize in North America, determining the density of adults in maize during the summer enables a prediction to be made of the expected level of damage from the progeny of the adult in the next maize crop in the following year. Thus Stamm *et al*., (1985) developed a threshold for central and northern Nebraska where, if there was an average of one or more adult per plant during August, then a precautionary soil insecticide was recommended for use in the next maize crop the following spring. This may seem a low threshold for action, but, depending upon diet, females can lay between 100 and 450 eggs each (Elliot *et al*., 1990). However, earlier work by Chiang *et al*., (1980) suggested that maize infested with eggs at densities of up to 600 or 1200 eggs/plant can still produce a near-normal yield.

In Hungary the larval damage threshold is reported to be 20-30 larvae per plant. Even in crops treated with insecticides such as terbuphos, damage occurred with 7.5% of the crop lodging (Cheek, 2003). In trials in Serbia, Baca *et al.,* (2006) reported lodging of between approximately 5% and 23%.

When considering grain yield, adults feeding on kernels at densities of up to 20 adults per ear, do not cause significant yield reduction and moderate levels of silk clipping can be tolerated (Capinera *et al*., 1986). However, it is the feeding damage to roots by larvae that is most significant.

Evidence from European countries suggests that there is a time lag of a number of years between the first finding of WCR and reports of economic damage[6]. WCR was first found in Europe in Yugoslavia (Serbia) in July 1992. Damage was reported as "severe" in 1996 although the damage was not quantified. In Serbian trials conducted over nine years and reported in 2006, Baca *et al.* (2006) reported maize grain yields falling from around between 8.5 - 9.0 t/ha to around 6.0 - 6.7 t/ha, representing yield losses of between approximately 25% and 30%.

[6] The time lag before any damage is seen seems to be widely accepted as at least 5 years after introduction (Cheek, 2003).

WCR was first detected in Hungary in 1995, and the first economic damage was reported in 2001 (EPPO, 1998). A survey of root damage was conducted in 919 fields covering 40,621 ha in Hungary during 2002. Larval damage was observed in 7,488 ha (18% of the survey area), root damage reached an economic level in 5,381 ha (13% of the survey area), and plant lodging was observed in several fields (EPPO, 2003). WCR was first observed in Croatia in 1995 and heavy damage was observed for the first time in the eastern part of Croatia in 2002 (EPPO, 2003). During 2003, five fields showed visible WCR symptoms in maize with between 26% and 91% of crop lodging. Yield losses were between 12.9% and 49.4% (Barcic & Bazok, 2004). In Romania, WCR was first reported in 1996. Some economic damage was sporadically observed in 2 out of 14 counties infested during 2002. WCR was first found in Italy in 1998. In 2002 a few dozen ha of maize in the province of Como suffered adult feeding damage on leaf and ears, and heavy root damage was observed for the first time (EPPO, 2003).

WCR has been found in Bosnia & Herzegovina (1996), Bulgaria (1998), Slovakia, Switzerland (2000), Ukraine (2001), Austria and France (2002) Belgium, the Netherlands, Slovenia and the UK (2003) but up to 2003 no economic damage had yet been reported in any of these countries (EPPO, 2003). However, the absence of economic damage reports does not mean that damage is not occurring because it is difficult to identify damage to maize at low population densities; chemical insecticides may mask potential damage and some lodging may be due to wind and rain. Alternatively, reports of economic impact may not have been published.

If WCR remains in England in fields where there is no maize rotation, over time, population densities could build up to damaging levels then maize plants could be harmed and have reduced kernel production, hence lower yields from the ears. Larval root feeding may cause lodging.

Detailed estimates of the potential financial impacts due to yield losses caused by WCR are given in Annex 5. Table 2 summarises three scenarios in which WCR spreads at different rates from its current locations near Heathrow and Gatwick airports. Where WCR persists in continuous maize, yield losses of between 5% and 10% are seen after 5 years.

<u>Methods and assumptions used: Industry costs of living with WCR (no statutory action)</u>

1. The area of maize grown does not significantly change in the next 20 years.
2. The area of maize suitable for development of WCR depends on climate and ranges stochastically from 76 ha in cool years, to over 119,000 ha in very hot years.
3. If climate allows, WCR spreads randomly from the south east of England averaging either 5, 10 or 20 km/ year

4. There would be no management costs.
5. Infested land would not have to be rotated.
6. Only continuous maize, grown for silage, would suffer any yield losses.
7. Yield losses of between 5% and 10% would occur five years after infestation.
8. Yield losses were applied to maize assumed to be worth £475 /ha.
9. No other costs would be incurred.

Caveats: The area of maize grown in the UK and the proportion for human consumption, i.e. cob maize, is likely to increase in years to come. New varieties, adapted to poor summers (lower temperatures and light levels in the UK than abroad), will enable maize to be grown further north and in cooler areas of the UK. Climate change scenarios suggest that England will have a much warmer summer allowing more maize varieties to be grown over a wider area than at present. Recent changes in EU subsidy payment schemes may also lead to changes in the area of maize grown.

Table 3: Net present value of maize yield losses accumulated over 20 years of WCR spread at three different rates (See Annex 5 for details).

Spread rate	Continuous maize area suffering yield losses in 20 years * (ha)	NPV of 5% yield losses (£'000)	NPV of 10% yield losses (£'000)
Moderate	6,599	614	1,227
Moderate-quick	17,263	1,822	3,646
Quick	17,480	2,821	5,642

* 20% of actual area occupied is assumed to be continous maize, where yield losses occur 5 years after first becoming infested (see text for further details).

17. What is the pest's potential as a vector of plant pathogens?

WCR can transmit and spread *Maize chlorotic mottle virus* (MCMV) (Gordon *et al*., 2001; Jensen, 1985). This virus is present in Argentina, Mexico, Peru, and the USA (Kansas, Nebraska and Hawaii) (Brunet *et al*., 1996)[7]. This virus has not been reported in Europe and it is therefore extremely unlikely that WCR reaching the UK from Europe will carry this virus although WCR arriving in the UK from countries where MCMV occurs could carry the virus.

In the USA, the virus acts synergistically with *Wheat Streak Mosaic Virus* or *Maize Dwarf Mosaic Virus* strains A or B to produce the economically damaging corn lethal necrosis disease (Uyemoto *et al*., 1980) with crop losses as high as 91% (Niblett & Claflin, 1978).

[7] http://image.fs.uidaho.edu/vide/descr464.htm

STAGE 3: PEST RISK MANAGEMENT

18. How likely is the pest to continue to be excluded from the PRA area?

Outdoors:	very Likely	Likely	Moderate likelihood	Unlikely	very Unlikely
				X	

WCR is already present though under official control. While specific pathways for entry to the UK remain unidentified, the possibility for further introductions can only be assumed to be high. However, as noted in section 13 (establishment potential) and Annex 3, under the existing climate, WCR would be close to the edge of its geographic range in England and it is not likely to be able to establish throughout the UK, so exclusion from parts of the UK will still be possible.

In protection:	very Likely	Likely	Moderate likelihood	Unlikely	very Unlikely
	X				

WCR is not a pest of protected environments (see 14.)

19. How likely are outbreaks to be eradicated?

very Likely	Likely	Moderate likelihood	Unlikely	very Unlikely
			X	

As with all findings of non-indigenous pests, the success of eradication will depend on how widely the pest is distributed when it is first found and the likelihood of preventing further entry. Trapping in maize growing regions of the UK and extensive trapping at and around sites known to be infested suggest that WCR is restricted to a small area of south-east England. Statutory rotation of infested maize fields should help control, if not eradicate the organism. The variable and sometimes unsuitable climate of UK could also aid eradication efforts. However, as noted in 18., since the pathway for entry remains unidentified and hence uncontrolled, the possibility for further introductions remains high.

<u>Eradication efforts in Europe</u>

Early reports suggest that eradication measures in 2002 seem to have been unsuccessful around Paris. In Italy, Plant Health Authorities have two eradication/ containment programmes in place; one in the Veneto region and the other in the Friuli-Venezia-Giulia region where WCR was found for the first time in 2002 in fields around the military airport of Aviano. Eradication/containment measures include (i) the prohibition of growing maize monoculture, (ii) the use of insecticides against adults in all maize fields, (iii) the prohibition of movement of fresh maize or soil in which maize has been grown the previous year, and (iv) chemical treatment of maize fields adjacent to fields where WCR has been found. These strategies have proved to be effective at preventing WCR from spreading in the Veneto region and populations were very low during 2002. Over the past five years there has been no significant spread from the initial outbreak area and population levels have decreased (EPPO, 2003). Control in Friuli-Venezia-Giulia is reportedly poor and the population large and increasing (report to EC Standing Committee on Plant Health, July 2003).

20. What management options are available for containment and control?

Cultural control: Crop rotation

Crop rotation is the major management option for WCR (Levay *et al*., 2006). Due to limited larval mobility, survival is restricted if eggs hatch and larvae emerge in a field previously sown with maize, but now in rotation (Branson & Kryson, 1981). Branson (1989) suggests that the soil dwelling larvae have a restricted movement ability and those that do not feed on a host within 24h have a much reduced chance of surviving to adulthood, e.g. only 55% of larvae survive to adulthood if they do not feed on host roots within 24h; less than 5% survive to adulthood if they do not find a host within 72h. Hibberd *et al*., (2003) suggest WCR larvae can move just less than 50cm so, under most circumstances, they should be able to find host roots only if they hatch within a field crop of a host. Thus crop rotation is recognised as the most effective method of control for WCR.

In the Swiss Canton of Ticino where crop rotation is enforced, the annual number of WCR captured during surveys has levelled off whilst in the neighbouring Canton of Grisons where maize is grown continuously, the number of WCR detected each year has risen sharply (Hummel *et al*., 2006).

In Serbia, WCR control is managed through rotation although an alternative crop to maize is grown either every second, third or fourth year, according to the growers own assessment of risk and in accordance to the cropping planned by neighbours. Crop plans are shared at the community level in a co-ordinated attempt to manage risk (Sivcev *et al*., 2006).

Cultural control: Delayed planting

In Lombardy, a WCR infested region of Italy, delayed planting of maize until late May or early June, resulted in acceptable levels of maize forage being grown and prevented adult WCR from emerging (Furlan *et al*., 2006), presumably since the lack of maize roots inhibited larval development.

Cultural control: Adding organic matter

Adding organic matter to the soil in fields of maize can stimulate the activity of micro-organisms and raise carbon dioxide levels in the soil making it more difficult for WCR larvae to locate plant roots (Fischer *et al*., 2006). Further reasearch to refine such a technique is required before incorporating it within a WCR management program.

Overcoming rotation

Maize and soya bean rotation has been the primary management strategy for control of WCR in the USA and Canada. In most instances, maize and soya bean have been rotated from field to field annually for decades. Prior to 1994, most egg-laying by WCR occurred in maize fields. However, in eastern Illinois and northern Indiana, WCR are now ovipositing a significant portion of their eggs in soya bean fields showing an evolutionary adaptation to crop rotation (Onstad *et al*., 2001). It appears that growers have inadvertently selected for a new strain of WCR by routine use of the maize and soya bean rotation. In such a low diversity landscape, restricted crop rotation selects for the expansion of host preferences (Gray *et al*., 1988). Since 1995, producers throughout east-central Illinois and northern Indiana have witnessed severe WCR larval injury to rotated maize due to the shift in the ovipositional behaviour of WCR. Wheat is an alternate host on which larvae feed and from which fecund adults can develop. However, US literature only refers to wheat as a host when researchers conduct experiments with alternate hosts. There are no reports of economic damage to wheat caused by WCR in US literature. The lack of literature concerning WCR on wheat may be due to the comparatively small area of wheat that is grown in the US corn belt where maize and soya bean predominate. However, wheat is a very commonly grown crop in the UK and is likely to feature in a maize rotation.

WCR Until the late 1980s WCR was not known to have extended diapause, unlike *D. barberi* whose eggs were known to be able to survive for over 4 winters before hatching (Levine & Oloumi-Sadeghi, 1991). However, unpublished work in the late 1980s (cited in Levine & Oloumi-Sadeghi, 1991) reported that a small proportion (less than 1%) of WCR eggs could hatch after 2 winters. Levine *et al*., (1992) were the first to publish a paper concerning extended diapause by WCR. Suitable crops that are not hosts and can be grown between maize crops include, field beans, peas, clover, vetch and sunflowers (Branson & Ortman, 1970). Whether a proportion of the European populations can extend there diapause is unclear. However, in regions commonly growing continuous maize, it is likely that there is greater selection pressure for the utilisation of additional hosts in allowing WCR to overcome crop rotation.

In a UK Maize Growers' Association survey in 1998, 80% of maize was in rotation, 20% was continuous maize. It is probably much the same now. If grown in rotation, maize will probably be with grass (for a dairy farm) or wheat (on a mixed farm). In the UK maize is grown for fodder, game cover and for human and small animal consumption in a heterogenous landscape, unlike in the corn belt of north America. Diverse landscapes, such as are found in the UK, will not encourage the adaptation of WCR to crop rotation (Guse & Onstad, 2003).

Chemical Treatments

The insecticide Dursban WG (Chlorpyriphos 75%) has been shown to provide good results against adults, both in US and European trials. For control purposes, it is recommended that Dursban WG is applied every 4 weeks until October. Specialist spray machinery may be required in a relatively tall maize crop, late in the season. This was a key limitation in the control programme used near Paris, and could also decrease gross margins by raising variable costs[8]. Of the three insecticides approved for use in the UK, only Dursban WG, with a 21 day harvest interval, has been shown to be effective against WCR. However, the use of chlorpyrifos (an organophosphate) is under review in the UK, and thus, future availability of chlorpyrifos products in the UK cannot be assured, despite support of the compound as part of the wider EU review of pesticide products.

In some other European countries, the soil insecticide Counter SG (terbufos) is recommended for use against larvae. This insecticide is not approved for use in the UK. Other soil applied insecticides recommended include carbosulfan, phorate and bifenthrin. Whilst these products are approved for certain field crops in the UK, they are not approved for use on maize, but some may offer potential for application on rotation crops, e.g. wheat.

The growing of continuous maize in North America and the widespread and regular use of insecticides to control WCR led to resistance to chlorinated hydocarbons developing in the late 1950's (Metcalf, 1976), and to other insecticides, including carbamates and OPs, more recently. The problem of insecticide-resistant corn rootworm remains, and field trials are carried out each year in the USA to evaluate the effectiveness of alternative soil insecticides for WCR control. In addition, management strategies now emphasise a more IPM-based approach, i.e. utilising rotation, scouting to determine the need for control, etc.

Trials on insecticide efficacy of soil treatments applied before sowing, at sowing or during the growing season, have been carried out in Serbia. It was concluded that best results were obtained before sowing with terbufos, lindane and bifenthrin; at sowing with terbufos, chlormephos, lindane and bifenthrin; and during the growing season with carbosulfan, terbufos and phorate. In other words, terbufos remains effective throughout. The best protection is obtained with a treatment at sowing (EPPO, 1996), and, ideally, a soil insecticide should persist for 6-10 weeks (Levine & Oloumi-Sadeghi, 1991).

Table 4 shows the top 12 active substances used on maize in the UK, by area treated in 2004/05 (Garthwaite *et al*., 2005). The major insecticide applied to maize was chlorpyriphos that has historically been used against frit fly (*Oscinella frit*), but is active against WCR. Insecticides registered for use on sweetcorn (outdoor), include lambda-cyhalothrin and pirimicarb.

[8] Insecticide sprays could be applied by contract sprayers, so individual farmers would not have to buy new equipment, but pay a contrator.

The Plant Health Service applied for, and obtained, an emergency specific off label approval (SOLA) for lamba-cyhalothin (Hallmark with Zeon Technology) for use on maize and maize stubble. However, this insecticide can only be used to control non-indigenous pests, and as such can be applied at an increased maximum individual dose of 200 ml product per hectare, required for control of WCR.

Table 4: The top 12 most widely used agrochemical sprays applied to maize in the UK in 2004/05, ranked by area treated. (Source: Garthwaite *et al.,* 2005)

No	Active Substance	Use of chemical	target pestS
1	Atrazine (now withdrawn)	Herbicide	Annual dicot. weeds
2	Bromoxynil	Herbicide	Annual dicot. weeds
3	Glyphosate	Herbicide	Annual dicot. weeds
4	Pendimethalin	Herbicide	Annual dicot. weeds
5	Bromoxynil / Prosulfuron	Herbicide	Annual dicot. weeds
6	Nicosulfuron	Herbicide	Annual dicot. weeds
7	Mesotrione	Herbicide	Annual dicot. weeds
8	other herbicides	Herbicide	Annual dicot. weeds
9	Fluroxypyr	Herbicide	Annual dicot. weeds
10	Chlorpyrifos	Insecticide	Frit fly / other insects
11	Metaldehyde	Molluscicide	Slugs and snails
12	Clopyralid	Herbicide	Annual dicot. weeds

Seed treatments

There are no seed treatments registered for use on maize in the UK. However, insecticide treated seed can be imported for planting in the UK. Available treated seed may lack adequate persistence for effective use under UK conditions, e.g. the efficacy of "Gaucho" seed treatment may be three weeks. "Cruiser" (thiamethoxam) seed treatments may also lack persistence, with an effective duration of three weeks from planting. Clothianidin may be more effective, lasting for up to six weeks (Matthews, pers. com.). Working in the WCR infested region of Italy, Furlan *et al*. (2006) showed that neither seed treated maize nor the application of soil insecticides during planting had any effect on the control of WCR.

Trapping

In countries where WCR is endemic, yellow sticky traps are primarily used for monitoring. At low population and high trap density, some population control may occur.

In Europe, where the pest is found in low numbers, pheromone traps, obtained from Hungary[9], have been used for monitoring purposes. These traps have been

[9] Plant Protection Institute, Hungarian Academy of Science, Budapest, Pf102, H-1525, Hungary. www.julia-nki.hu

successful in catching WCR in a range of European countries. A range of traps is available (see Table 5). The PAL traps are particularly suited to early monitoring and providing first-detection results and have been used for initial detection by the majority of European countries. This type of trap, however, only attracts males, thus information regarding females cannot be obtained in this way. As a consequence, the Hungarian Plant Protection Institute has developed a trap which, in addition to the pheromone, contains a floral volatile, and is capable of trapping both sexes (PALs). Results have been less successful than expected, since females need to be in close proximity to the traps, and, when the pheromone is combined with the floral volatile, it does not attract the males as successfully as the pure pheromone traps. The pure pheromone trap from Hungary, therefore remains the most effective monitoring method. In Germany 283 traps in total have been placed in 147 point of entry monitoring sites. The recommended distance between traps is 1 km (or less). However the attractivness range is only 15-20 m. Traps should not be placed within 20 m of each other due to disruption effects. The pheromone dispenser should be replaced every 4 to 6 weeks. The sticky sheet may need to be changed even more frequently if large numbers of insects are being caught. There are two types of trapping mechanism associated with the pheromone trap. Funnel pheromone traps have a permanent trapping capacity, unlike the sticky pheromone trap, however the design is irrelevant for first detection purposes.

Table 5: Features of three *Diabrotica virgifera virgifera* pheromone traps available from Hungary

	Trap name / type		
Characteristics	PAL	PALs	VARs
Target:	males	males & females	males & females
Volatile:	pheromone	pheromone + plant floral volatile	pheromone
Type of trap:	sticky cloak trap	sticky cloak trap	funnel trap (non sticky, high catching capacity
Duration of trap effectiveness:	4-6 weeks	4-6 weeks	one year
Maintenance:	no maintenance, single use of 4-6 weeks	no maintenance, single use of 4-6 weeks	change bait every 4-6 weeks
Purpose:	detection/ monitoring	detection/ monitoring	detection/ monitoring and mass trapping
Cost (Euro):	3.44	4.13	5.74
replacement pheromone (Euro):	N/A	N/A	2.99

Breeding maize for resistance to WCR

Since the 1930's there have been various research programs investigating the possibility of developing maize varieties resistant to rootworm damage. Such work is currently being conducted in Croatia, Serbia and the USA (Hibbard, 2006; Ivezic *et al*., 2006; Bohn & Davis, 2006).

Use of GM maize

In the USA genetically modified (GM) maize varieties have been developed for controlling corn rootworms. The Monsanto variety YieldGard Rootworm corn MON863 was first approved in 2003 with use on around 162,000ha of maize. Since then it has been widely adopted with an estimated 2.5 million ha planted in 2006. Other varieties include Herculex RW (Dow: Event DAS-59122-7 corn) that contains Cry34Ab1 and Cry35Ab1 proteins. Syngenta has also recently developed a variety of GM maize-MIR604 that expresses a modified Cry3A protein. All Syngenta GM-maize also incorporates a seed treatment. GM products protect early season damage from adults at pollination, but all hybrids (Monsanto, Dow and Syngenta) have been found with significant root damage later in the season, which may cause lodging and yield losses.

In Europe, Spain has been using GM maize against European corn borer, *Ostrinia nubilalis* since 1998 (MON810 from 2004 and Syngenta 176 from 2005), with 15% (75,000ha) of total maize production using Bt (*Bacillus thuringiensis*) corn. However, this variety is not effective against WCR. Hungary is the only European country testing rootworm Bt maize cultivars, in very small plots (500 square metres) scheduled for planting until 2008.

21. The risks presented by the UK to other countries in the EU if WCR were to establish

WCR is well established in parts of south eastern and Central Europe, including some EU Member States, e.g. Hungary (since 1995), Italy (since 2000) and Slovakia (since 2001).. The primary source for future spread into other EU MS will remain the populations based in Continental Europe or even North America rather than from any WCR populations that become established in the UK.

Results from Miller *et al.* (2005) indicate that three out of five analyzed western European WCR outbreaks did not originate from the WCR infested region of Central Europe, but from the USA. Moreover, the introductions to western Europe were independent from each other and from the initial European introduction thus WCR has been introduced from the USA at least three other times since it was introduced to Serbia.

Speculation that adult WCR are attracted to airports lights, or kerosene fuel vapour, and are subsequently carried and spread via aircraft, was quashed following publication of results of trials in Hungary that failed to show that such lights or fuel acted as an attractant to WCR (Baufeld *et al*., 2006).

Recognising that WCR had been introduced to Europe on at least four separate occasions, Miller *et al*. (2005) suggested that European regulatory agencies and authorities should pay more attention to controlling pest species on intercontinental flights. While specific pathways for spread remain unidentified, the possibility for further introductions along such pathways remains high. Less than 3% of the maize in England is grown within 20km of our two major international airports (Heathrow and Gatwick) and the likelihood of WCR spreading from the UK to mainland Europe via aircraft is very slight in comparison to the likelihood of spread from regions of Europe with well established WCR populations and already sharing a terrestrial frontier with MS which do not have such well established populations.

Nevertheless, if WCR established in the UK there is a very small possibility that individual beetles could fly back into mainland Europe. Annual spread of between 80 and 100 km has occurred in Europe, thus it appears that spread to mainland Europe from the UK is within the range of WCR and hence is possible. However, it is highly likely that spread rates of 80 to 100km per year occurred with adults touching down to land intermittently, rather than by flying such distances in a single flight. Thus the English Channel and North Sea will present a considerable barrier to WCR spreading to Europe from England[10] although strong winds following weather fronts can carry mature beetles significant differences over bodies of water (Grant & Seevers, 1989).

[10] Less than 4% of all maize in England is grown in Kent and East Sussex, the counties closest to mainland Europe.

Further work that would reduce uncertainties

Area of PRA	Uncertainties	Further work that would reduce uncertainty
Taxonomy	The taxonomy of this organism is understood.	-
Pathway	No specific pathways into the UK have been identified. There may be an association with air transport.	Identification of specific pathways.
Distribution	European distribution is changing as the organism spreads.	Continued monitoring and sharing of information.
Establishment	Annual area suitable for establishments Effect of climate change	Further analysis of establishment potential in relation to maize growing regions. Degree days required to complete development related to soil temperature profiles.
Spread	Rate of spread in the UK.	Further modelling linking spread to more detailed understanding of establishment.
Impact	The location and area of continuous maize grown in the UK. Ability to adapt to develop on wheat or other cereals. Population densities causing impacts on yield/ quality	Mapping of continuous maize. Development studies to include fecundity. Trails to measure yield responses to pest pressure.
Management	Cost of management options.	Analysis of growers' costs and options for WCR management.

CONCLUSION OF THE PEST RISK ANALYSIS

Western corn rootworm, one of the most important maize pests in the northern hemisphere, has been found near European airports on several occasions and has now been found close to two airports in south east England.

Under current climate conditions in the UK, WCR appears to be near the edge of its range, although by 2050, large areas of England are predicted to be suitable for this species. However, predictions of climatic suitability for WCR are not easy to make because all stages, except the adult, live in the soil and WCR's environmental responses which have been reported in the literature are difficult to extrapolate to UK conditions primarily because we have no comprehensive soil temperature profiles for the maize crop in the UK. Nevertheless, comparisons of air and soil temperatures at different depths from locations south of London indicate that:

(a) WCR could get through its life cycle in most if not all of the last thirty years in southern England, and

(b) the warmer summer temperatures in the most recent years have greatly increased the likelihood of this occurring. Outside southern England, the likelihood of WCR completing its life cycle rapidly diminishes.

Although WCR may well have established in southern England, population densities are likely to remain low unless the area grown without rotation increases dramatically from its current national level of about 20% and summer temperatures continue to increase. In the autumn, most adult female beetles lay eggs in the soil of the field in which they have emerged and also disperse to lay their eggs in other maize fields. If a non-maize crop is grown where eggs are laid it is very unlikely that the majority of larvae will survive to adulthood. A number of cereals may be poor alternative hosts and although adults could develop from larvae feeding on their roots, further research is required to determine the extent to which cereals such as winter wheat can maintain significant WCR populations. Rotation is widely practised to control WCR, though north American WCR populations have shown a capacity to overcome rotation with soya bean.

Experiences in central Europe, where the summers are much hotter and WCR has been present for over ten years, suggest that significant economic impacts, due to larvae feeding on roots and adults on the flowers causing yield losses and crop lodging, only occur after several years of continuous maize cropping. In areas where economic damage has occurred farmers are now switching to growing maize in rotation, despite the lower economic return from alternative crops.

Maize is increasingly grown in England and Wales, not only as silage but also for grain, for sweet corn and as a cover for game. As our climate warms and cold tolerant varieties improve, this crop is likely to become of greater importance. If WCR became established in the UK, and continuous maize cropping becomes an increasingly important strategy used by maize growers, WCR populations, assisted by climate change, will increase and cause economic losses in maize without rotation. Of course, our ability to control maize pests may improve and an agreement to allow the sowing of maize expressing genes for the insecticide, *Bacillus thuringiensis*, would influence the risk assessment for WCR in the UK (Moellenbeck *et al*., 2001).

A range of management options for the control of WCR are available. Of the three insecticides approved for use in the UK, only Dursban WG, with a 21 day harvest interval, has been shown to be effective against WCR but it is under review and its future availability is uncertain.

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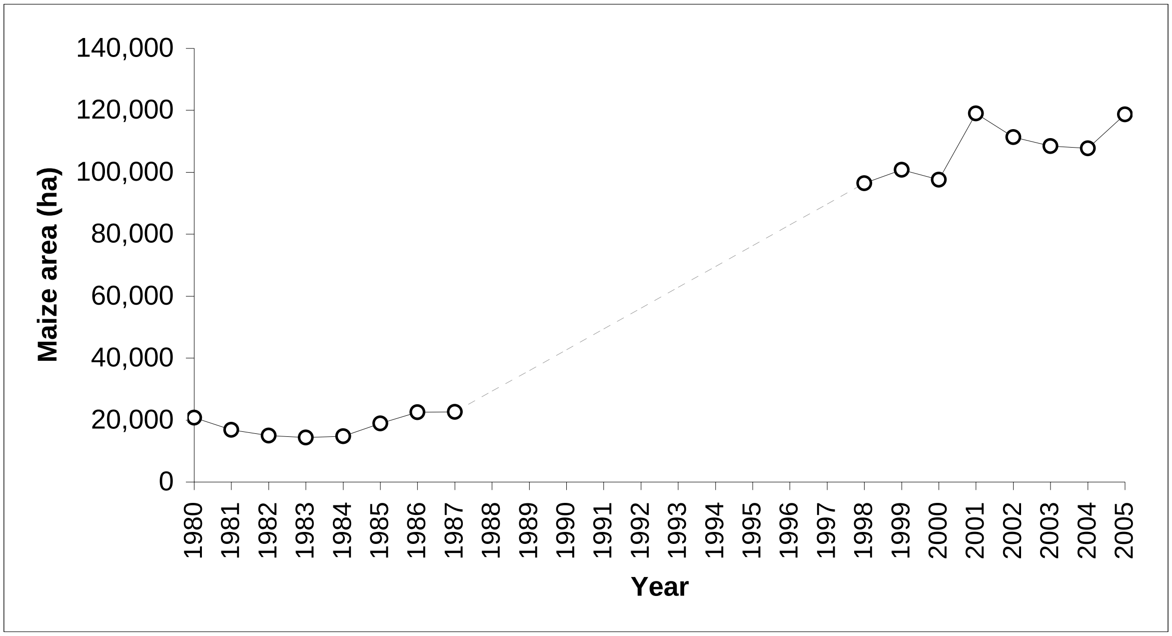
ANNEX 1

UK MAIZE PRODUCTION

The vast majority of maize (*Zea mays*) harvested for commercial purposes in the UK is used for cattle feed. A small proportion is grown to produce sweetcorn for human consumption and an additional minor use is to produce grain for small animals, e.g. pigeons & corn fed chicken (Nix, 2006). Before it is harvested as a forage crop, maize can also be used in the field as a standing crop within which a maze is constructed. Thus it becomes a source of income for farmers from tourist leisure activities. This study focuses on the value of maize used for cattle feed and the potential economic consequences resulting from damage by WCR.

Figure A1: Chart showing the area of maize grown in England 1980 - 2005. Source Defra



Note: between 1988 and 1997, beet, mangolds and other crops were included with maize hence the broken line which links annual maize area.

One of the reasons for the large increase in area of maize grown in England, up from around 20,000 ha pa during the 1980s to over 100,000 ha pa from the late 1990s is due to the availability of new varieties of maize which are suitable for growing with lower light levels and lower temperatures.

ANNEX 2

WESTERN CORN ROOTWORM FOOD PLANTS / HOSTS

WCR larvae are limited to feeding on the roots of monocotyledons. Plants which WCR are known to feed on, or have been tested in trials are listed in Table A2 below.

Table A2: Hosts on which WCR larvae feed and mature to adulthood.

binomial name	common name	Occurs in UK?	Reference
Agropyron elongatum	tall wheatgrass **	No	Branson & Ortman, 1970
Agropyron intermedium	intermediate wheatgrass **	No	Branson & Ortman, 1970
Agropyron smithii	western wheatgrass	No	Cheek, 2003
Agropyron trachycaulum	slender wheatgrass **	No	Branson & Ortman, 1970
Agropyron trichophorum	pubescent wheatgrass **	No	Branson & Ortman, 1970
Digitaria sanguinalis	hairy finger grass	Yes	Cheek, 2003
Echinochloa crus-galli	cockspur	Yes	Cheek, 2003
Eragrostris curvula	African lovegrass **	Yes	Branson & Ortman, 1970
Eragrostis trichodes	sand lovegrass **	No	Branson & Ortman, 1970
Eriochloa gracilis	wooly cupgrass	No	Chege *et al.,* 2005.
Eriochloa villosa	hairy cupgrass	No	Cheek, 2003
Panicum capillare	witch-grass	Yes	Chege *et al*., 2005.
Panicum miliaceum	common millet	Yes	Moeser & Vidal, 2003
Setaria faberi	bristle grass	Yes	Cheek, 2003
Setaria pumila (=*glauca; lutescens*)	Yellow bristle-grass **	Yes	Moeser & Vidal, 2003; Breitenbach *et al*., 2005
Setaria italica	foxtail bristle-grass **	Yes	Branson & Ortman, 1970
Setaria verticillata	Rough bristle-grass *	Yes	Moeser & Vidal, 2003; Breitenbach *et al*., 2005
Setaria viridis	Green bristle-grass *	Yes	Branson & Ortman, 1970; Breitenbach *et al.,* 2005
Triticum aestivum	Wheat **	Yes	Branson & Ortman, 1970
Triticum spelta	Spelt **	Yes	Branson & Ortman, 1970
Zea mays	Maize	Yes	

(**) In experiments that measured the number of eggs laid by females, significantly fewer eggs are laid by females feeding on hosts marked ** than by those developing from maize.

(*) In experiments that compared larval development, development was significantly reduced for larvae feeding on hosts marked * compared with those feeding on maize.

More recent work in the US by Clark & Hibbard (noted by Cheek, 2003) recorded that 21 out of 28 species of grassy weeds supported WCR larval growth at least to the third instar (L3).

Notes on the distribution of grass hosts (sources Tutin *et al.*, 1980; Preston *et al*., 2002, unless stated).

- *Agropyron elongatum* is a synonym for *Elymus elongatus* which occurs in southern and south-eastern Europe. It is not present in the UK.
- *Agropyron intermedium*; *Agropyron trichophorum* are both synonyms for *Elymus hispidus* which occurs in Europe as far north as central France, and up to 56°N in Russia. Not present in the UK.
- *Agropyron smithii* does not occur in Europe. It is not present in the UK.
- *Agropyron trachycaulum* is a synonym for *Elymus trachycaulus* which occurs in Russia where it is widely cultivated for fodder. It is not present in the UK.
- *Digitaria sanquinalis* is native to southern Europe and the Mediterranean. Present in the UK spreading as a weed of garden centres, also found on rubbish tips.
- *Echinochloa crus-galli* native of Europe, Asia and N. America. Occurs as a casual in the UK on rubbish tips, wate places and cultivated ground.
- *Eragrostris curvula* is a north American grass. Occurs as a casual on waste ground and rubbish tips. Few British records.
- *Eragrostis trichodes* is a north American grass not present in Europe.
- *Eriochloa villosa* occurs in the southern Ukraine and south east Russia. It is not present in the UK.
- *Panicum capillare* is present in the UK in waste places and rubbish tips. It is cultivated in gardens for its beautiful panicles.
- *Panicum miliaceum* occurs in the UK as a casual in waste places, and in woodland around pheasant feeding areas. Occurs as a contaminant of maize.
- *Setaria lutescens* is a synonym for *Setaria pumila*. Present in southern and central southern Europe and as far north as the Netherlands. It is not present in the UK.
- *Setaria faberi* is native to E Asia but has naturalised in a few places in the UK in waste places and rubbish tips.
- *Setaria pumila* (= *glauca,* = *lutescens*) present in the UK in cultivated ground and on waste places. Probably native to the Mediterranean and SW Asia.
- *Setaria italica* is present on rubbish tips, in docks and waste ground in lowland areas of the UK. Elsewhere it is often found in warm-temperate and subtropical regions.
- *Setaria verticillata* a casual in waste places, rubbish tips, verges and waste ground and rarely occurs as a weed on arable land. Native to Eurasia.
- *Setaria viridis* a casual in cultivated ground, waste places, rubbish tips and verges. Native to Eurasia.
- *Triticum spelta* is a hardy type of wheat traditionally grown in mountainous regions. It is now restricted to parts of Spain and central Europe (de Rougemont, 1989) but may be grown in small parts of the UK for specialist bread making.

There is a clear adaptive potential for a small proportion of the population to survive on grass field weeds or grasses on set-aside land. This increases the likelihood of reintroduction of the pest in short-term rotations and hinders complete eradication of any outbreak.

ANNEX 3

ARE CLIMATIC CONDITIONS SUITABLE FOR *DIABROTICA VIRGIFERA VIRGIFERA* ESTABLISHMENT IN THE UK?

1. Introduction

The methods used for determining whether an area is climatically suitable for the establishment of an organism are essentially as follows:

- Climatic Matching – comparing climatic conditions in a species' current range with those in the PRA area.
- Climatic Responses, Accumulated Temperature Budgets and Phenology Modelling – extrapolating results from experiments, e.g. on the relationship between development and temperature, and determining whether climatic conditions are suitable for an organism to complete its life cycle in the PRA area, e.g. are there enough summer day degrees for development and will winter temperatures enable survival?
- CLIMEX – combining the two approaches, so climatic responses are matched and configured to the current distribution and extrapolated to the PRA area.

The key information required is therefore: (a) detailed knowledge of a species' current distribution and the extent to which this is limited by climate and (b) data on a species responses to climatic conditions, especially temperature.

Although there is a considerable and growing literature covering all aspects of the distribution and biology of WCR, the data on its distribution and climatic responses is difficult to interpret because:

- Although the current distribution of WCR in North America and Europe is well documented, since it is rapidly spreading in both areas, it is difficult to judge the extent to which the current limits to its distribution are caused by unfavourable climate or simply by the fact that WCR has yet had sufficient opportunity to move further.
- Except for the adult stage, all parts of its life cycle are spent in the soil (eggs are 10 – 20 cm deep) (see Annex 8). The climatic data which are generally used for matching climates, climatic responses, phenology modelling and CLIMEX are all based on measurements above ground. There is no simple relationship between air and soil temperatures because environmental conditions in the soil depend on ground cover, soil type, water retention capabilities, conductivity and other factors.
- The estimated environmental responses in the literature, particularly those which have been used to attempt to predict WCR phenology in the soil based on air temperatures, show considerable variability. Soil type, maize variety and genetic variation in WCR populations clearly all play a role.

2. Methods

To take account of the difficulties noted in the introduction, a number of approaches have been adopted:

2.1 CLIMEX

CLIMEX has been applied by France (Reynaud, 1998 and pers. comm.), Germany (Baufeld *et al.*, 1998 and pers. comm.) and the Netherlands (Stigter, pers. comm.) to predict the distribution of WCR in Europe. Climatic responses calculated originally for the soil have been used even though CLIMEX only uses air temperatures. The key parameter chosen is an 11°C minimum threshold for development. The minimum number of degree days for the completion of WCR's life cycle is given as 670.

CLIMEX comes loaded with 1931-1960 monthly averages and gives an estimate of establishment potential for stations round the world (285 for Europe). There are two main disadvantages: (a) the climate has warmed up considerably since 1931-1960, and (b) stations may be unrepresentative of the area around them where crops are grown. We have, accordingly, loaded CLIMEX with 1961-1990 climate interpolated to a 0.5° latitude/longitude grid by the Climate Research Unit, University of East Anglia (New *et al.*, 1999).

2.2 Accumulated Temperature Budgets

Assuming, as above for CLIMEX, that WCR needs a minimum of 670 degree days at a base of 11°C for development from the egg to the adult stage, then annual development success or failure can be calculated from sequences of temperature data. Maize is usually harvested by the end of October, so this can be considered as the cut-off date. Ideally, we would have many annual sequences of recent daily maximum and minimum temperature data at 10 cm depth for a large number of weather stations in the maize growing areas in the UK. Since such data are not available we have used the following data sets, described further below:

- 5 km Resolution UK Grid Cells of Mean Monthly Temperatures
- Daily maximum and minimum air temperatures at Gatwick Airport
- 9 AM temperatures at 30 cm depth from Gatwick Airport

2.2.1 *5 km Resolution UK Grid Cells of Mean Monthly Temperatures*

This mean monthly dataset has recently been provided by the UK Meteorological Office (2006) and gives interpolated mean monthly climatic parameters at 5 km resolution for each year between 1961 and 2005. Mean monthly temperatures were loaded directly into a GIS and annual accumulated temperatures calculated initially for 1995 - 1997.

The maize distribution for England was provided by the Defra Economics and Statistics Division also at a 5 km resolution (Defra, 2003) (see fig. A3 i). Using the GIS mask facility, temperature data for only the 5 km grids where maize is grown in 2001 (Fig. A3 ii) were displayed. The area of England where the annual accumulated temperature over base 11°C exceeded 670 was then calculated. Two measurements were made: all 5 km squares and only the 5 km squares where maize is grown.

The National Assembly for Wales (2001) provides maize statistics for Wales (6,316 ha) and its regions. However, Neil Stuart (pers. comm.) notes that: “These figures come with quite severe health warnings. The small areas, small numbers of holdings, and the fluid nature of the activity make the data quality of these estimates rather dubious. They will be fine to identify broad trends, but not for specific small area detail. Perhaps the most helpful thing that we can give you is a map drawn up by our GIS colleagues (see Fig. A3 iii). This map was generated by excluding: land over a given height, land with a severe slope, and land of inappropriate soil type and quality. Comparison of the "potential" map with the local authority values shows that the land in Pembrokeshire is generally not used for maize. This is probably because a better return can be obtained from other crops.”

2.2.2 *Daily maximum and minimum air temperatures at Gatwick Airport*

The spread of WCR in Europe has been by adult flight and through man’s assistance. At three locations in both Italy and France, WCR has first appeared in the vicinity of airports. It therefore seems logical, as a matter of priority, to predict WCR’s establishment potential at Gatwick, the principal airport south of London. Daily maximum and minimum air temperatures for 1970-1997 were obtained from the British Atmospheric Data Centre (2003) and the day degrees over base 11°C calculated using a method which takes account of situations where the base temperature lies between the daily maximum and minimum (Baker, 1980). Both the annual accumulated temperature and the date when 670 degree days was reached were recorded. Daily data for 1998-99 were obtained from the USA National Climatic Data Center (2003).

2.2.3 *9 AM temperatures at 30 cm depth at Gatwick Airport*

The British Atmospheric Data Centre (2003) also provides an almost complete run of soil temperature data at 30 cm depth collected at 9 AM for Gatwick Airport for two years (1995 and 1997). Recognising that the study of soil temperature profiles and their relationship to temperatures above ground is a complex subject and requires a much more detailed investigation using many years of data from the same location, preliminary answers to the following questions have been explored:

- How do soil temperature accumulations at 30 cm compare with air temperatures?
- How do soil temperature accumulations at a depth of 30 cm compare with those at 10 cm, where developing stages of WCR might be expected?
- How close are the 9:00 AM daily records to the daily mean which is needed for degree day calculations?

To determine how soil temperature accumulations at 30 cm compare with air temperatures, the daily 30 cm soil data were compared with air temperatures from Gatwick Airport.

To determine how soil temperature accumulations at a depth of 30 cm compare with those at 10 cm, daily 9:00 AM soil temperatures at 10 cm and 30 cm from Wisley Botanic Gardens, 25 km north east of Gatwick Airport, were compared.

To determine how close the 9:00 AM records are to the daily mean, hourly soil temperature data for 1997 at 10 cm depth were obtained for Kenley Airfield, 20 km north-east of Gatwick from the British Atmospheric Data Centre (2003). A daily mean was calculated and compared to the 10:00 AM record (the 9:00 AM record is missing).

2.3 Climatic Matching

The latest distribution map of WCR in Europe (EPPO, 2003) shows both the areas where WCR is present and also the area where economic impacts have occurred. Daily climatic data from a location in the centre of the area where economic impacts have occurred, Novi Sad Rimski (45° 02'N, 19° 51'E) in Northern Yugoslavia, were downloaded from the USA National Climatic Data Center (2003) and accumulated temperature budgets base 11°C calculated for 1994-1999. These annual temperature budgets were compared with those obtained in the UK.

3. Results

3.1 CLIMEX

Ostensibly CLIMEX indicates that establishment is possible at a few locations in southern England under 1931-1960 mean temperatures (see fig. A3 iv) but not in any of the 0.5° latitude/longitude grid cells with mean monthly 1961-1990 data (fig. A3 v). The minor differences in the CLIMEX parameter files provided by Reynaud, Baufeld and Stigter do not alter these results. Examination of the CLIMEX output files reveals that the number of degree days above 11°C available for development is below the 670 threshold in all the 0.5° latitude/longitude grid cells with mean monthly 1961-1990 data. Having determined that accumulated temperature is critical, we have explored this aspect further outside CLIMEX by using datasets with both a higher spatial resolution (actual weather station data and climatic data interpolated to 5 km^2 grid cells) and temporal resolution (daily data and annual monthly means) using both air and soil temperatures (see below).

3.2 Accumulated Temperature Budgets

3.2.1 *5 km Resolution UK Grid Cells of Mean Monthly Temperatures*

Figs A3 vi, A3 vii and A3 viii display the annual 1995, 1996 and 1997 accumulated temperatures at 5 km resolution for the UK. Figs A3 ix and A3 x and A3 xi show the same data only for grid cells where maize is grown in England. Grid cells with accumulated temperatures greater than or equal to 670 are coloured in red or purple. The numbers of 5 km grid squares where accumulated temperatures reached 670 for the UK as a whole and just for the squares where maize is grown are given in Table A3 i. For the latter data, the number of hectares of maize in these cells has also been calculated.

Table A3 i: The number of 5 km grid squares where accumulated temperatures reached 670 for the UK as a whole and just for the squares where maize is grown

Year	Number of 5 km cells in the UK in which the accumulated temperature is greater than or equal to 670 with a base of 11ºC	Number of 5 km cells in England where maize is grown in which the accumulated temperature is greater than or equal to 670 with a base of 11ºC.	Maize area potentially affected, based on 2000 maize distribution (‘000 ha)
1990	1,667	784	39.2
1991	103	24	1.2
1992	1,244	547	27.35
1993	32	3	0.15
1994	386	111	5.55
1995	3,605	1,804	90.2
1996	154	38	1.9
1997	1,765	824	41.2
1998	876	376	18.8
1999	2,482	1,154	57.7
2000	966	404	20.2
2001	2,814	1,244	62.2
2002	1,050	336	16.8
2003	3,790	1,732	86.6
2004	2,643	1,142	57.1
2005	3,713	1,685	84.25

3.2.2 *Daily maximum and minimum air temperatures at Gatwick Airport*

Table A3 ii gives both the annual accumulated temperatures base 11ºC for Gatwick Airport from 1970-1999 and the dates at which an accumulated temperature of 670 were achieved.

Table A3 ii: The annual accumulated temperatures base 11ºC for Gatwick Airport from 1970-1999 and the dates at which an accumulated temperature of 670 were achieved

Year	Gatwick Airport Annual Accumulated Temperature Base 11ºC	Date at which Gatwick Airport Accumulated Temperature Base 11ºC reaches 670	Year	Gatwick Airport Annual Accumulated Temperature Base 11ºC	Date at which Gatwick Airport Accumulated Temperature Base 11ºC reaches 670
1970	790	16-Sep	1985	692	15-Oct
1971	733	3-Oct	1986	660	-
1972	567	-	1987	730	25-Sep
1973	767	-	1988	702	20-Oct
1974	559	-	1989	991	16-Aug
1975	770	-	1990	899	25-Aug
1976	925	15-Aug	1991	763	14-Sep
1977	611	-	1992	820	27-Aug
1978	664	-	1993	707	23-Sep
1979	648	-	1994	837	30-Aug
1980	650	-	1995	1032	14-Aug
1981	678	1-Nov	1996	783	13-Sep
1982	818	6-Sep	1997	974	20-Aug
1983	864	27-Aug	1998	799	7-Sep
1984	786	13-Sep	1999	868	31-Aug

Fig. A3 xii gives the annual variation in accumulated temperature and the trend line clearly shows how the years have become warmer over the 30 year period (maximum 1032 in 1995). For nine years out of the thirty analysed, annual accumulated temperatures were less than 670. Fig. A3 xiii shows that the date when 670 degree days are achieved is becoming earlier (earliest 14th August in 1995). An insignificant amount of degree days above 11ºC is accumulated in November and December, so there is little difference between the annual accumulated temperature total and that reached at the end of October, by which time the maize is harvested.

3.2.3 *9 AM temperatures at 30 cm depth at Gatwick Airport*

Fig. A3 xiv shows that, as expected, the 30 cm soil temperatures recorded at 9:00 AM are unaffected by the rapid daily changes in the air maxima and minima, retaining a higher level of warmth in the autumn and early winter and taking longer to warm up in spring and early summer. Fig. A3 xv shows that, in 1995, a

172 higher annual accumulated temperature (1204) is reached at 30 cm compared to that above ground (1032). In 1997, the only other year with comprehensive data, a 156 higher annual accumulated temperature (1130) is reached at 30 cm compared to that above ground (974).

Fig. A3 xvi shows, from data collected at Wisley in 1999, that temperatures at 10 cm are warmer than those at 30 cm depth in summer and colder in winter (annual mean –0.7 ± 2.7ºC). The annual daily temperature profile can be seen in Fig. A3 xvii. The annual accumulated temperature at different depths can be seen in Fig. A3 xviii and summarised in table A3 iii, showing that, at 30 cm depth, a reduction of approximately 100 in the annual accumulated temperature compared to the total at 10 cm can be expected.

Table A3 iii: The annual accumulated temperatures at Wisley at different soil depths in 1999

	Soil depth				
	10 cm	20 cm	30 cm	50 cm	100 cm
Annual Accumulated Temperature base 11ºC	1066	886	961	989	839

Fig. A3 xix shows the difference between the daily average at 10 cm depth and the record at 10:00 AM at Kenley Airfield. Over the whole year, the 10:00 AM reading is 0.9 ± 0.2ºC lower, with the difference (maximum 1.7ºC) being greatest in summer. This gives an annual accumulated temperature of 852, 190 lower than if the daily mean (1042) is used.

This analysis of soil temperature profile data suggests that the 30 cm 10:00 AM annual accumulated temperature total at base 11ºC could be increased (a) by approximately 100 to make it similar to the total expected at 10 cm, where WCR eggs, larvae and pupae are found and again (b) by approximately 200 to account for the difference between the measurement at 9:00 AM and the daily mean. However, these weather station records are taken under a grass sward and a different soil temperature profile can be expected under a growing crop of maize. Although the effect will increase as the crop grows, the maize will act as a considerable temperature buffer, suggesting that the 30 cm soil depth temperature under a grass sward may be similar to the 10 cm soil depth temperature under a maize crop. If the difference in depths is discounted, we only need to increase the annual accumulated temperature budget to account for the difference between the 9:00 AM temperature and the mean daily temperature, adding some 200 day degrees to the total.

Annual accumulated temperatures based on above ground measurements were approximately 165 day degrees below those taken at 9:00 AM, 30 cm underground. If the timing of the measurements and the difference in depth between 30 cm and 10 cm where WCR occurs are taken into account, then the annual air temperatures may be expected to be approximately 250 day degrees below the 10 cm soil temperature accumulations. If this sum is added to the 1970-1999 annual accumulated above ground temperatures at Gatwick Airport, then the 670 threshold for WCR to complete its life cycle is exceeded in every year.

3.3 Climatic Matching

Accumulated temperatures above 11ºC for Novi Sad Rimski, a weather station representative of an area where WCR has been present for nearly ten years and has caused considerable economic impact, during 1994-1999 are given in Table A3 iv. With a mean of 1506, they are nearly double the mean (882) for Gatwick Airport during the same period.

Table A3 iv: The annual accumulated temperatures base 11ºC at Novi Sad, Yugoslavia in 1994-1998

Year	Annual Accumulated temperatures base 11ºC
1994	1733
1995	1514
1996	1354
1997	1418
1998	1597
1999	1419

4. Discussion

Predictions of the establishment of species which spend most of their life cycle in the soil are always difficult because of the problems associated with estimating the environmental factors at a particular depth in the soil under a crop as it grows from data collected above ground and from limited soil data obtained under standardised conditions. This preliminary analysis using a very limited dataset indicates the directions which would be undertaken by a more detailed investigation. Such an investigation could follow Elliot *et al*., (1990), who adapted models by Gupta *et al*., (1983; 1984) of soil temperature profiles related to above ground temperatures, the soil type and the crop, (also used by the program WEEDCAST, North Central Soil Conservation Laboratory (2003)). Other models by Hoffmann *et al*., (1993) and Luo *et al*., (1992) could also be parameterisised for UK maize growing conditions.

As has been seen, temperatures in the soil vary considerably with depth. The depth at which the eggs and larvae occur will thus have a considerable influence on their rate of development. Their depth may depend on cultivation and soil moisture. Eggs and pupae have been found as deep as 22.5 - 23 cm while larvae may occur from 0-15 cm (summarised by Bergman & Turpin, 1986).

Considerable uncertainty remains as to the choice of the minimum threshold of 11°C and the limit to the annual accumulated temperature being set at 670 which arises from investigations by Jackson & Elliot (1988). WCR is extremely adaptable and environmental response data taken from populations in Ontario, at the current northerly limit to its distribution in North America, and from European populations would be more appropriate. The CLIMEX parameters used by European risk assessors predicts that WCR could find suitable climatic conditions considerably further north and south of its distribution in North America (Krysan & Miller, 1986) (see Fig. A3 xx). While this may be due to other factors, e.g. the limits of maize cultivation (in the north) and competition from other *Diabrotica* species (in the south), this may imply that the climatic response parameters in CLIMEX need modification. Jackson & Elliott (1988) and Davis *et al*., (1996) highlight the difficulties of estimating the minimum threshold for development and the appropriate number of degree days for the development of each life stage, adapting these to air temperatures while taking account of substantial regional differences.

Synchrony with the host plant is also important for pest survival. Delayed planting may decrease root damage since hatching larvae can survive only a few days without feeding on suitable hosts. If planting is delayed until early June, root damage is negligible and soil insecticide usage is not warranted (Musick *et al.*, 1980). Adult emergence may extend over a period of up to a month, increasing the probability that maize varieties of different maturity classes are still likely to be attacked by a proportion of the emerging adults seeking pollen, silk and young kernels for food (Stavisky & Davis, 1997).

5. Conclusions on Climatic Suitability

Under current climate conditions, WCR, appears to be at the edge of its range in the UK. Predictions of climatic suitability for WCR are not easy to make because all stages, except the adult, live in the soil and WCR's environmental responses which have been reported in the literature are difficult to extrapolate to UK conditions primarily because we have no comprehensive soil temperature profiles for the maize crop in the UK. Nevertheless, comparisons of air and soil temperatures at different depths from locations south of London indicate that (a) WCR could complete its life cycle in most if not all of the last thirty years and (b) the warmer summer temperatures in the most recent years have greatly increased the likelihood of this occurring. Outside southern England, the likelihood of WCR completing its life cycle rapidly diminishes.

To explore the effect of climate change, accumulated temperatures were calculated at 5 km resolution for four UKCIP02 climate change scenarios predicting climates in 2050 under low, medium low, medium high and high emission scenarios (Hulme *et al.,* 2002). See Figures A3 xxi, A3 xxii and Table A3 v. Fig A3 xxiii shows the similarity in area at risk between the hot year of 1995 and 2050, when such hot years are likely to be the norm rather than the exception.

Table A3 v: Comparison of the number of 5 km grid cells in the UK climatically suitable for *Diabrotica virgifera virgifera* under future climatic conditions based on a threshold of 670 degree days above a base of 11ºC.

Year	Number of climatically suitable 5 km cells
1995	4852
2050 UKCIP02 high emissions scenario	5137
2050 UKCIP02 medium high emissions scenario	4667
2050 UKCIP02 medium low emissions scenario	4407
2050 UKCIP02 low emissions scenario	3879

Annex 3 Figures

Fig. A3(i)

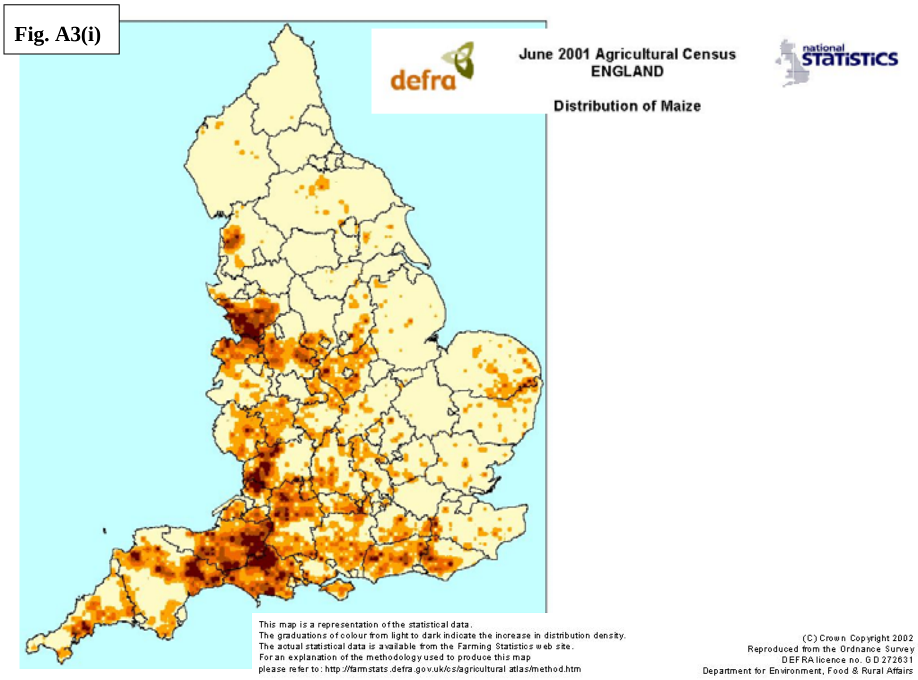


Fig. A3(ii)

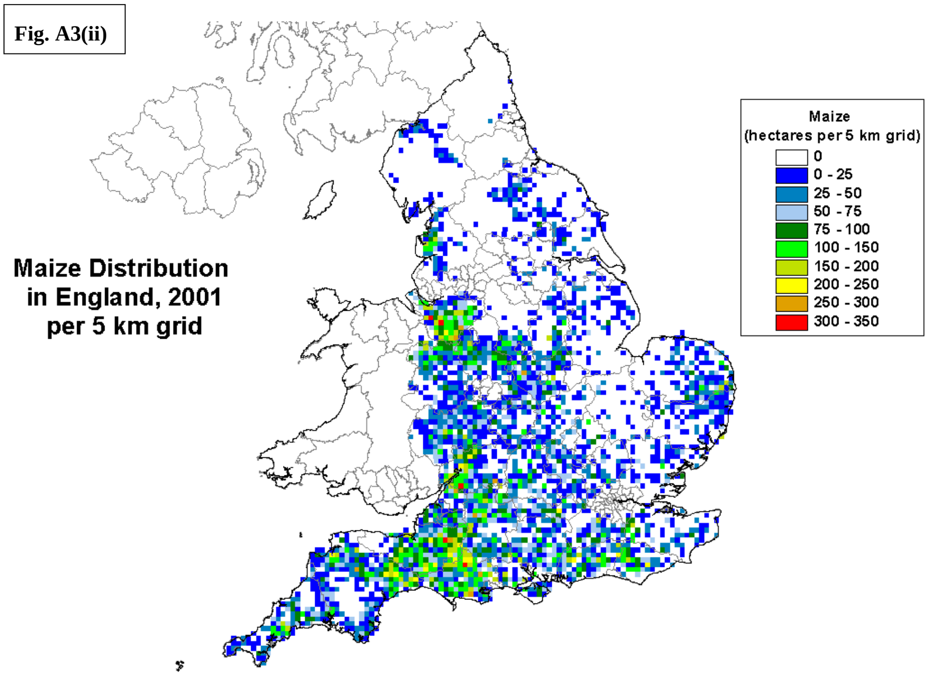
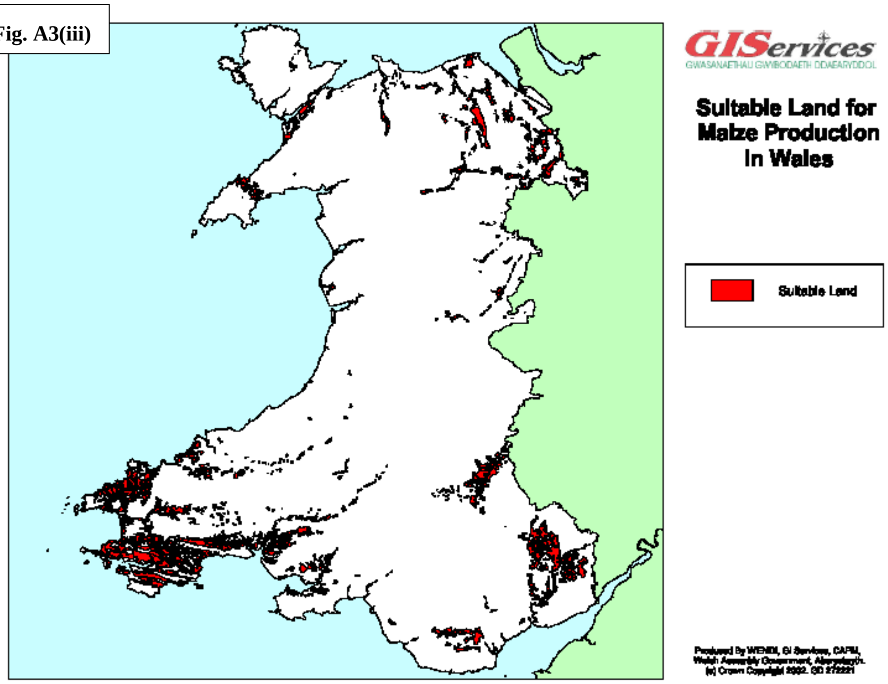


Fig. A3(iii)


GIServices
GWASANAETHAU GWYBODAETH DDAEARYDDOL
Suitable Land for Maize Production in Wales
Suitable Land

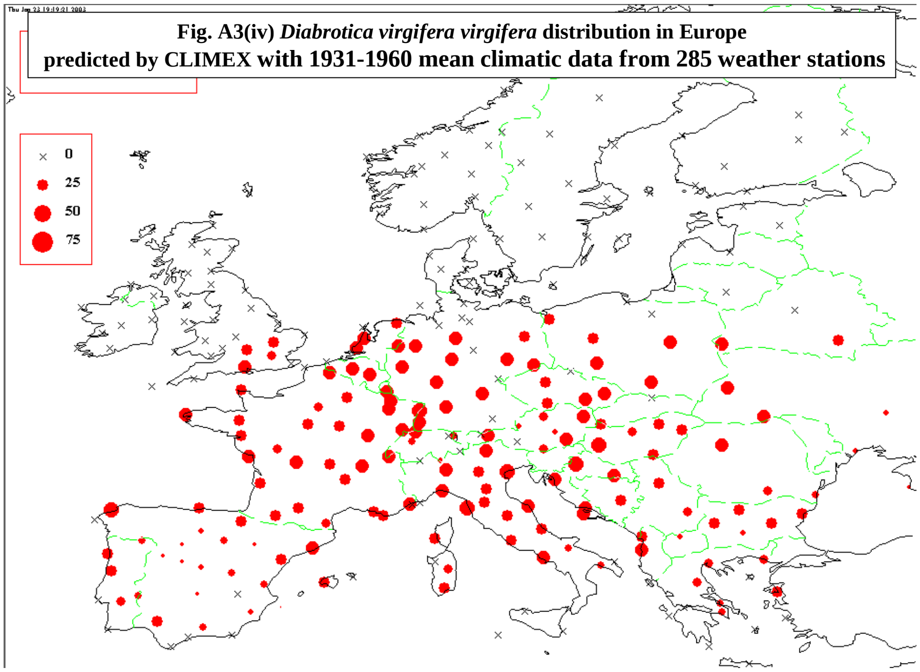


Fig. A3(iv) *Diabrotica virgifera virgifera* distribution in Europe predicted by CLIMEX with 1931-1960 mean climatic data from 285 weather stations

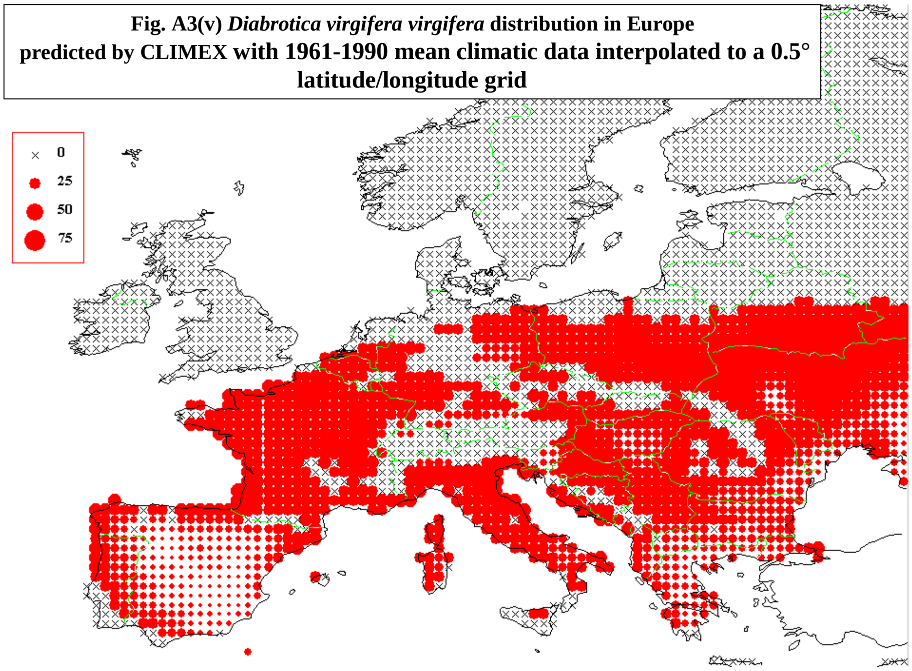
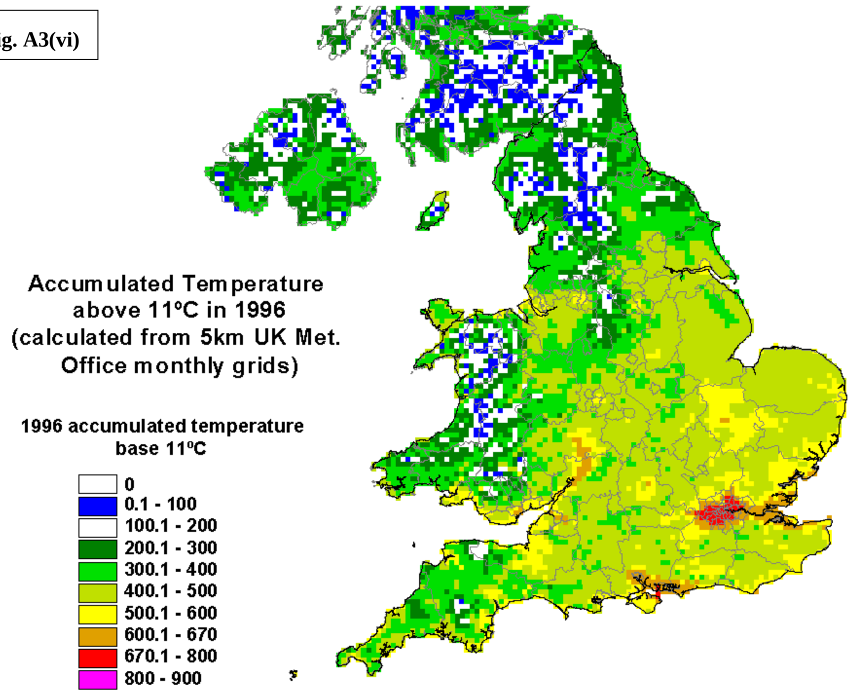


Fig. A3(v) *Diabrotica virgifera virgifera* distribution in Europe predicted by CLIMEX with 1961-1990 mean climatic data interpolated to a 0.5° latitude/longitude grid

Fig. A3(vi)



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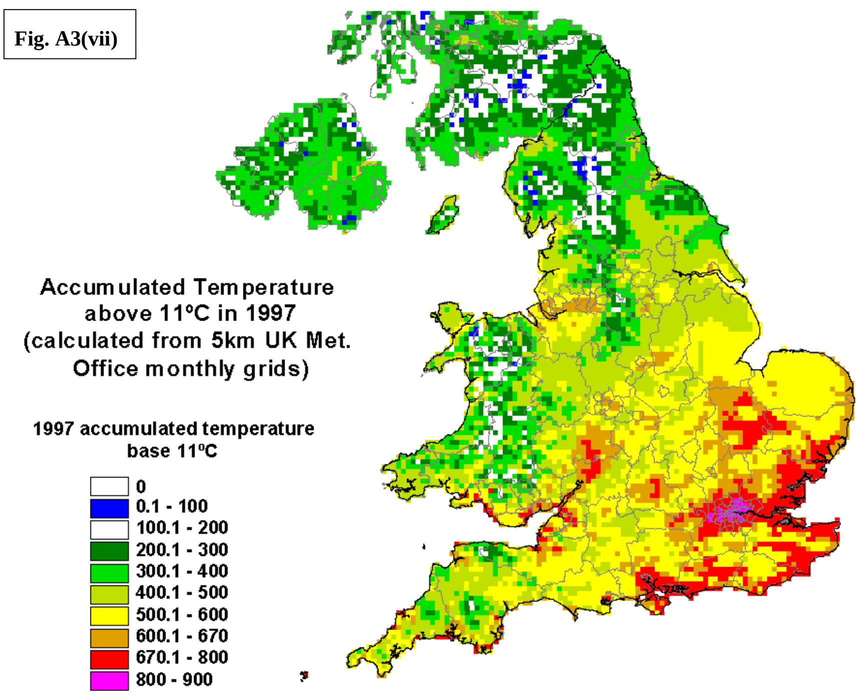

Fig. A3(viii)

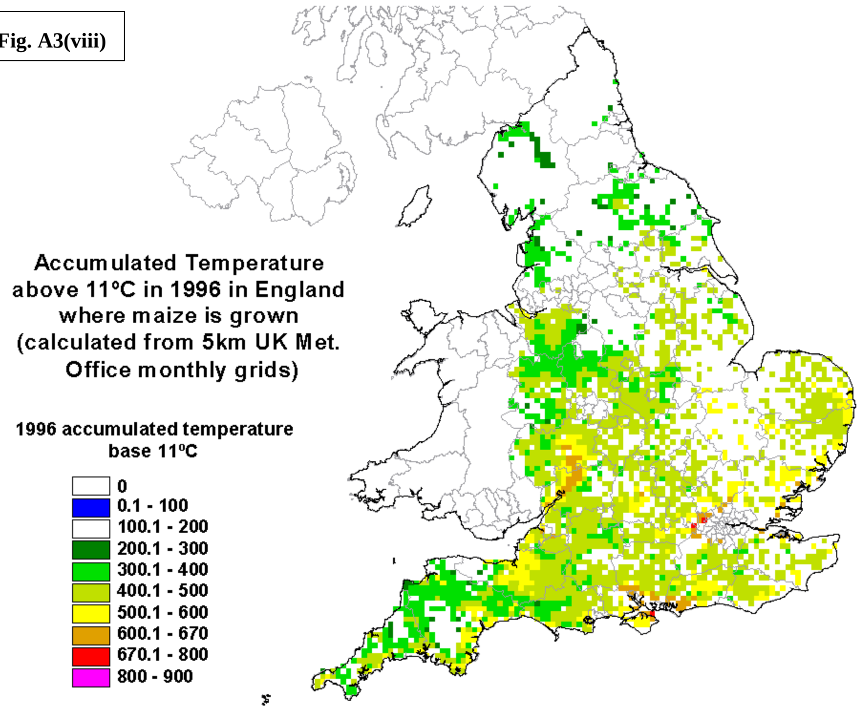

Fig. A3(ix)

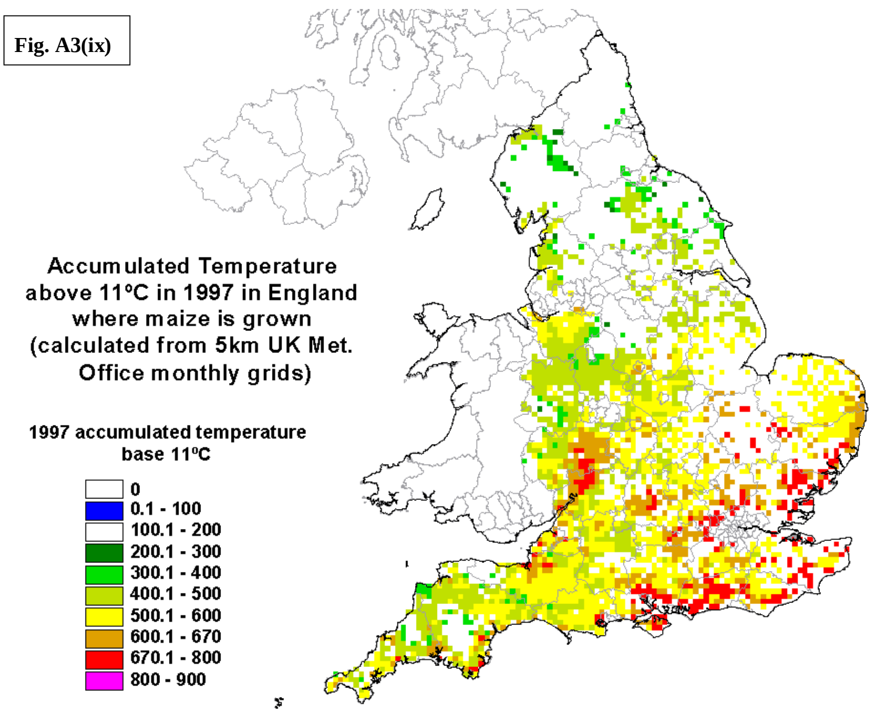

Fig. A3(x)

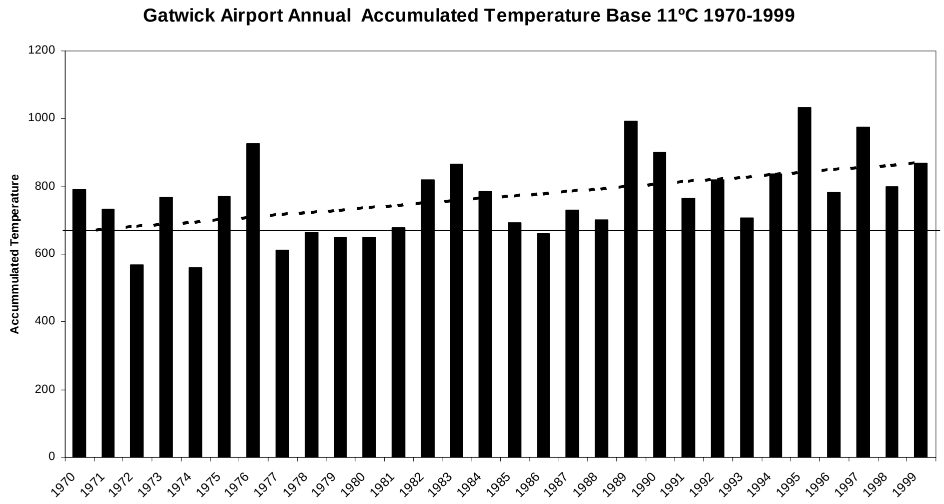

Fig. A3(xi)

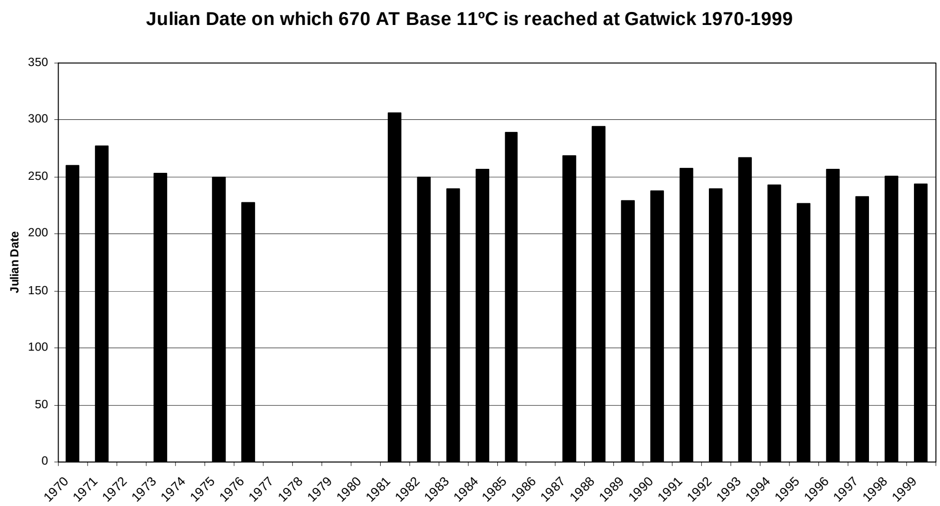

Fig. A3(xii)

Air and Soil Temperatures, Gatwick Airport 1995

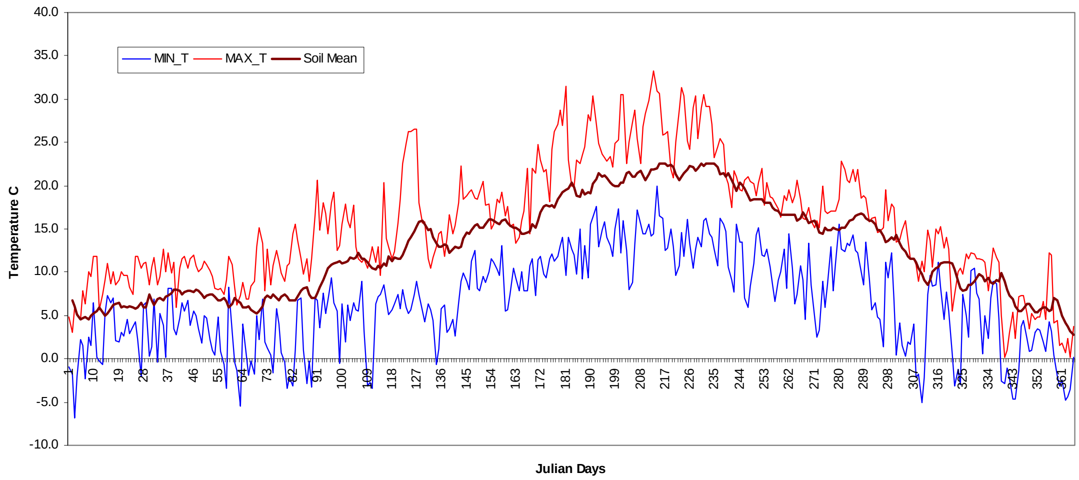

Fig. A3(xiii)

Gatwick Airport: Air and Soil (30 cm depth) Cumulative Day Degrees, 1995

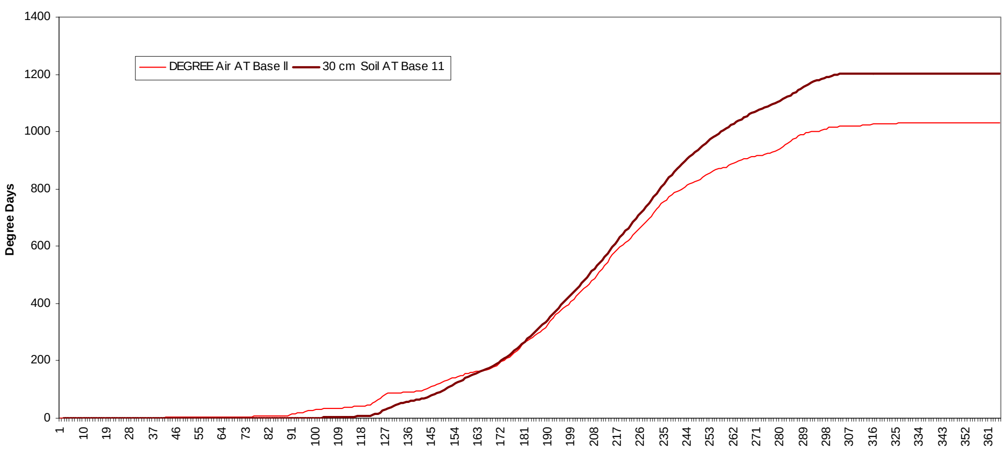

Fig. A3(xiv)

Wisley 1999: Daily Difference between Soil Temperatures at 10 cm and 30cm depth

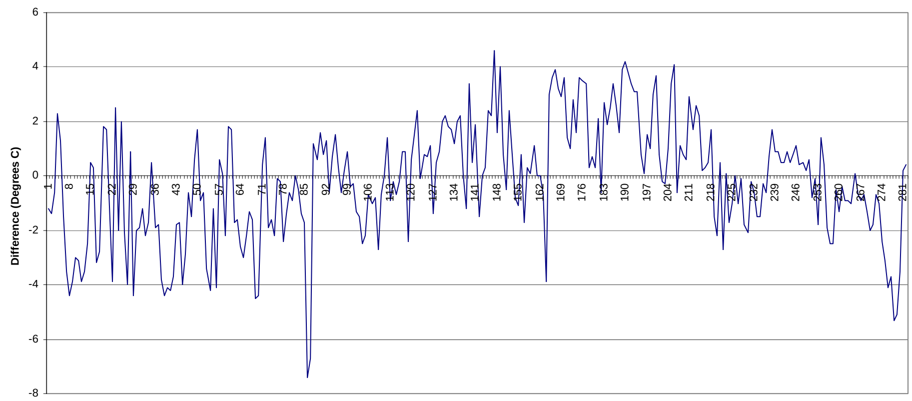

Fig. A3(xv)

Wisley 1999: Daily mean temperatures at different soil depths

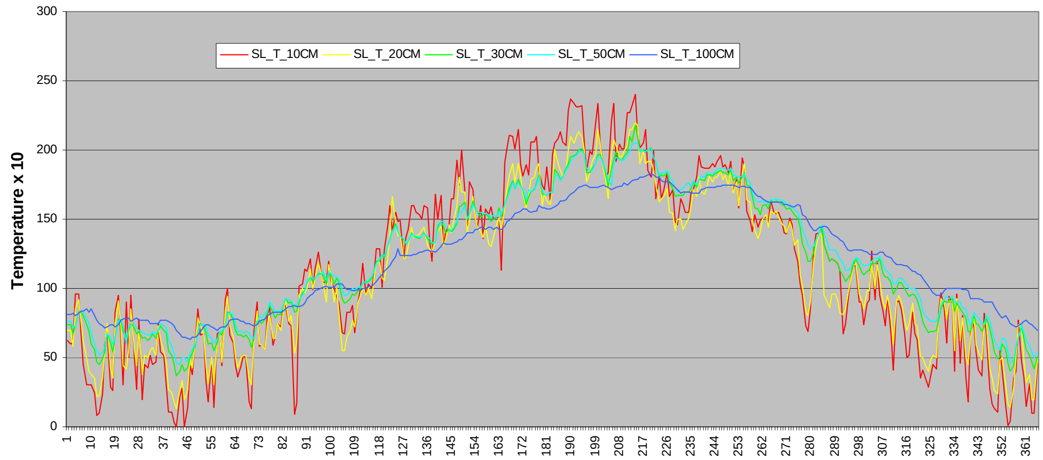

Fig. A3(xvi)

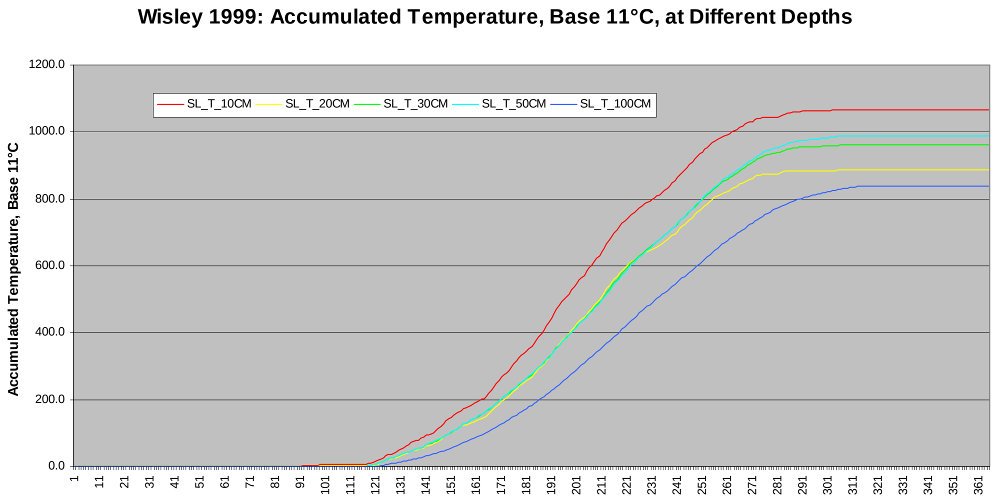
Wisley 1999: Accumulated Temperature, Base 11°C, at Different Depths
SL_T_10CM
SL_T_20CM
SL_T_30CM
SL_T_50CM
SL_T_100CM
Accumulated Temperature, Base 11°C
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
1
11
21
31
41
51
61
71
81
91
101
111
121
131
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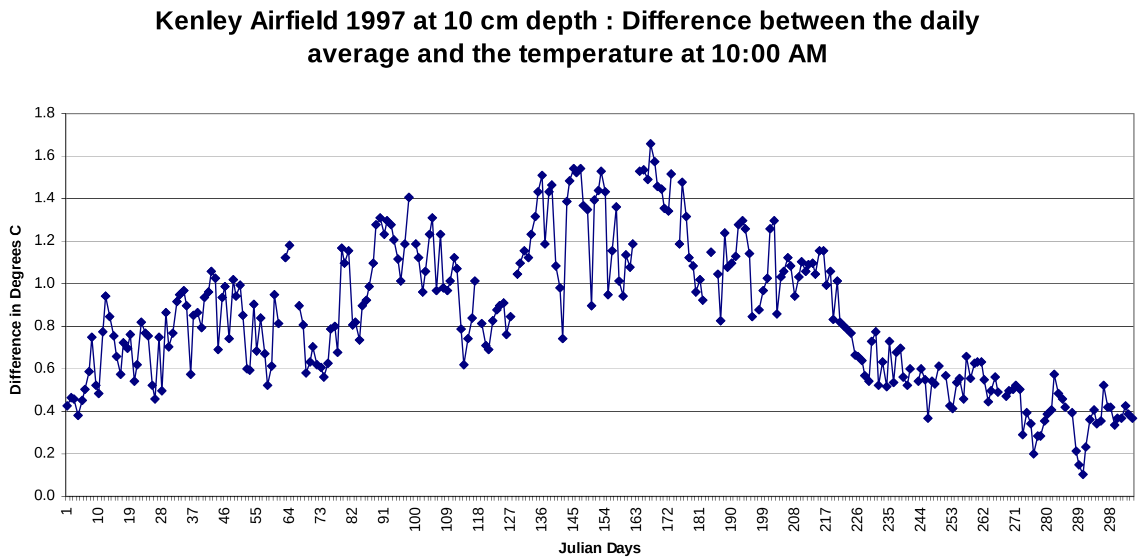
Fig. A3(xvii)


Kenley Airfield 1997 at 10 cm depth : Difference between the daily average and the temperature at 10:00 AM
Difference in Degrees C
Julian Days
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

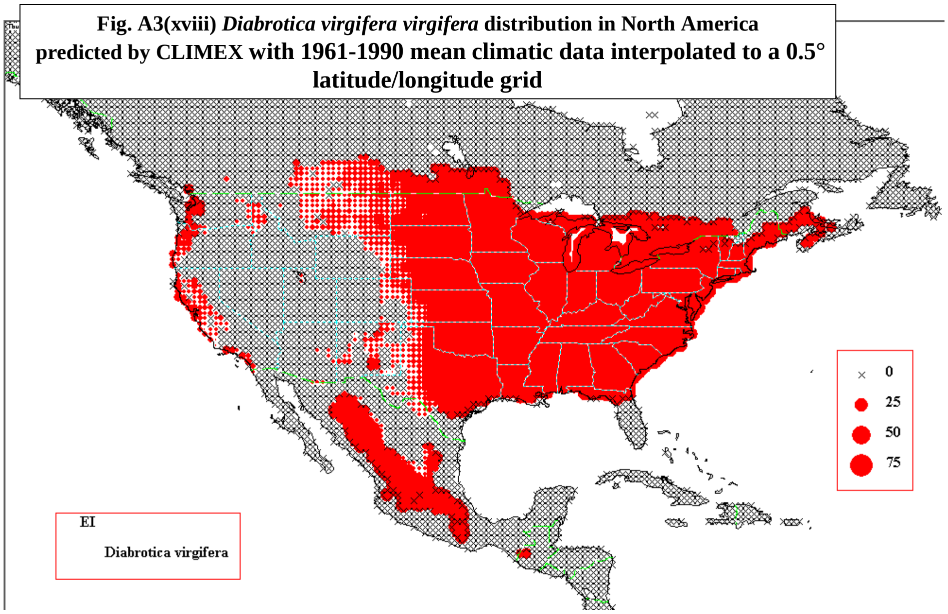


Fig. A3(xviii) *Diabrotica virgifera virgifera* distribution in North America predicted by CLIMEX with 1961-1990 mean climatic data interpolated to a 0.5° latitude/longitude grid

ANNEX 4

Rate of spread of *Diabrotica virgifera virgifera* in Europe

Examining the map given in Annex 10, it is clear that WCR has spread faster northwards than towards the east or west. Table A4 below shows the rate of spread in three different straight lines a) in a northerly direction, from the source towards Bratislava, b) eastwards towards Romania and c) westwards towards Bosnia-Herzegovina.

Table A4: Rate of spread of *Diabrotica virgifera virgifera* in Europe, 1992-2002 (derived from Map Annex 10)

Year	Spread northwards (distance in the year)		Spread eastwards (distance in the year)		Spread westwards (distance in the year)	
	miles	km	miles	km	miles	km
1992	0	0	0	0	0	0
1993	5	9	11	18	11	18
1994	11	18	14	22	14	22
1995	55	88	5	9	19	31
1996	16	26	47	75	8	13
1997	30	48	22	35	14	22
1998	3	4	16	26	22	35
1999	49	79	2	3	0	0
2000	19	31	9	15	55	88
2001	52	84	5	9	19	31
2002	5	9	0	0	8	13
Minimum	3	4	0	0	0	0
Mean	25	40	13	21	17	27
Maximum	55	88	47	75	55	88

ANNEX 5

THE POTENTIAL ECONOMIC IMPACT OF *DIABROTICA VIRGIFERA VIRGIFERA*

1. Uses of maize

Maize is primarily of economic importance in the UK as silage to feed cattle (dairy and beef). A small proportion of maize is grown to produce sweetcorn for human consumption and grain for small animals, e.g. pigeons and corn fed chicken (Nix, 2006). It is also grown to produce flour for use in baby food. Finally it can be grown in a mix with other crops, or alone, to provide game cover. Table A5.1 provides estimates of the area of maize grown in the England, Wales and Northern Ireland, and of the associated value of each type of maize.

Table A5. 1: The area and value of maize grown according to its use. (Data from various sources)

Intended use	Gross margin [(a)] (£/ha)	Area grown ('000) (ha)	Value (£'000)	% of total area
Forage maize	475[b]	120[c]	57,000	89.6
Game cover	900	10[d]	9,000	7.5
Maize grain (e.g. pigeon food)	410	3[e]	1,230	2.2
Sweetcorn (human consumption)	975	1[f]	975	0.7
		134	68,205	100.0

(a) Based on ADAS (2004)
(b) Prices can range from £250-£800/ha according to potential yield and local market conditions, although £425-£525 would be more typical (Nix, 2006). The mid-point of £475 is used in the analysis.
(c) based on Annex 1
(d) The game cover area varies according to sources. See text for details.
(e) Nix (2006) estimates perhaps 3,000 ha of grain maize is grown. This has increased from the 1,500 ha estimated by Nix (2002)
(f) UK DEFRA stats http://www.defra.gov.uk/esg/work_htm/notices/janveg.pdf (area was actually recorded as 1,170 ha but the figure has been rounded down in Table 1)

Maize grown for silage accounts for around 90% of the total area of maize grown. Game cover accounts for approximately 7.5% of maize area and sweetcorn under 1% of the area, the remainder is for grain or flour production.

Sweetcorn and grain maize crops are usually rotated as a matter of course, usually to provide a break for other crops such as brassicas (to avoid club root), so WCR is likely to have little or no impact (ADAS, 2004).

2. Maize area at risk from western corn rootworm

Assumptions and methods

1. Under current climate conditions, WCR, appears to be at the edge of its range (Annex 3).

2. Data for an unusually warm year (1995), an unusually cool year (1996) and a more typical/average year (1997) (Annex 3 Table A3 i; Annex 12), were used to identify the area suitable for the development of WCR. As the climate is warming, the choice of a "typical" year or average of years has become more difficult. By overlaying the area of maize from Defra June census data on top of the suitable climatic areas in a GIS, the endangered area of maize becomes apparent, e.g. see Annex 3, Figs A3 (viii) and (ix).

3. The area of maize suitable for development of WCR depends on climate and ranges stochastically from 76 ha in cool years, to over 119,000 ha in very hot years.

4. For the purposes of the analysis, it was assumed that the area of maize grown does not significantly change over the next 20 years.

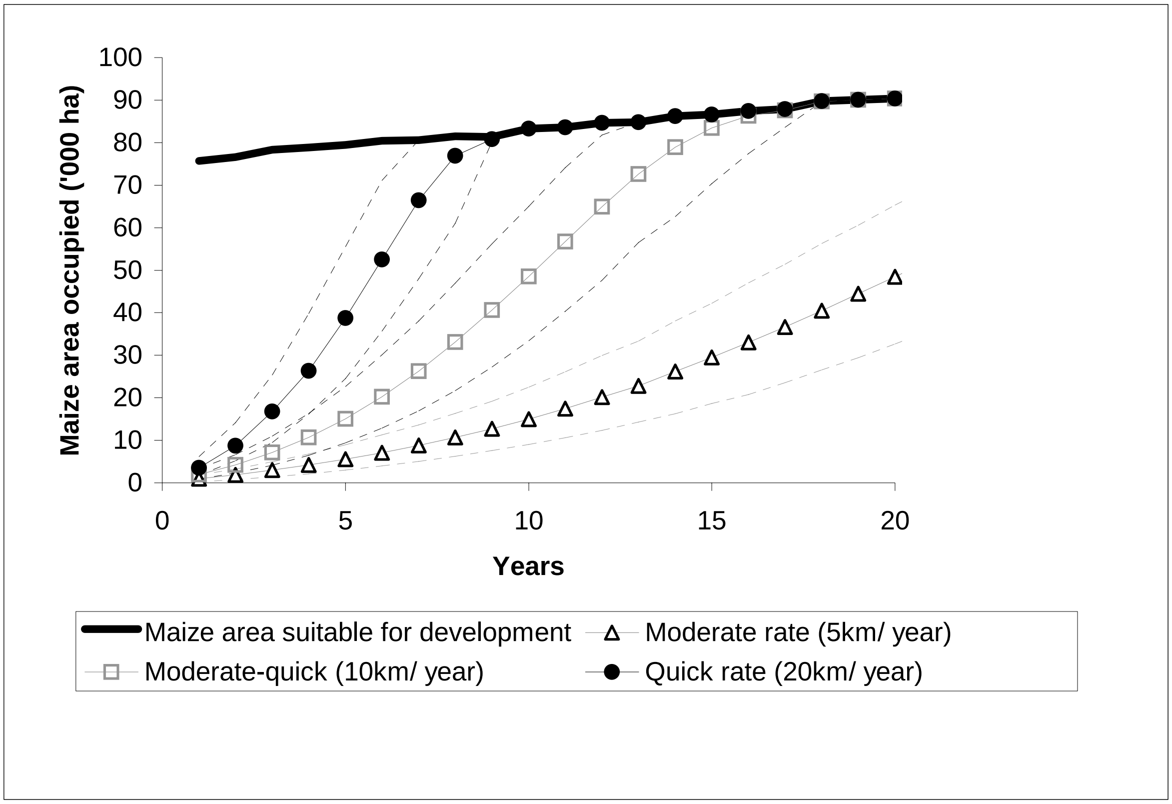
5. In a situation where there was no statutory control of WCR, it is assumed that WCR would spread and over time build up populations in fields of continuous maize before economic impacts were seen. To take account of the time taken to spread from the current outbreak sites, three different distributions of rates of spread were envisaged. (1) A moderate rate was expected to range from a minimum of 0 km/ year; typically be 5 km/ year and have a maximum of 15 km/ year. (2) A moderately-quick rate of spread was expected to have a minimum of 5 km/ year; typically be 10 km/ year and have a maximum of 25 km/ year. (3) The quickest spread was expected to range form 10 km/ year; typically be 20 km/ year and have a maximum of 40 km/ year.

6. A stochastic Monte Carlo simulation model combined the maximum area that could be occupied within each year (determined by climatic conditions) and used the rate of spread to determine the actual area infested each year. The simulation was run 10,000 times for each rate of spread. The simulation model showed that WCR would spread from the outbreak site until a cooler year reduced the endangered area, and then the national population of WCR would shrink to infest a smaller area.

7. Summarising the 10,000 iterations of the simulation, with quick spread, on average, WCR would spread for about eight years then occupy just over 80,000 ha of maize each year. However, each annual mean area occupied has a wide standard deviation associated with it, due to the randomness of climate.

Figure A5. 1: The mean area of maize occupied as WCR spreads at either a "moderate rate" (5km /year); a "moderate-quick" rate (10km /year); or a "quick" rate (20km/ year) ('000ha).

Note that WCR populations will only build to damaging levels in continuous maize, which is assumed to be approximately 20% of the area shown.



<u>Interpretation of Figure A5.1</u>

- Summarising the 10,000 iterations of the simulation, the average area of maize suitable for WCR development slowly increases each year as the climate changes.
- With quick spread, WCR spreads for about eight years then occupies an area of just over 80,000 ha of maize each year. The area potentially occupied then only increases in line with climate change. Since the majority of the area occupied is rotated, WCR populations only grow to damaging levels in continuous maize (assumed to be 20% of the area occupied).
- With moderate-quick spread, WCR spreads for about 15 years then occupies an area of almost 90,000 ha of maize each year. As above, the majority of this is rotated, so WCR populations only grow to damaging levels in 20% of the area occupied.
- With moderate spread, WCR continues to spread each year and after 20 years occupies less than 55,000 ha. As above, the majority of this is

rotated, so WCR populations only grow to damaging levels in 20% of the area occupied.

3. Damage to maize by western corn rootworm
3.1 Damage reports in the USA and Europe

In the USA and Europe, south of Paris, most maize is grown for flour or oil production and the cobs, and grains or kernels on them, are the plant parts that are of greatest value. WCR is one of the two most serious pests of continuous grain maize in North America (Oerke *et al*., 1994) where the cost of soil insecticides used to control larval damage to maize roots, aerial sprays to reduce adult damage to maize silks, and crop losses, approach $1 billion annually (Metcalf, 1996). This is approximately equivalent to $33 (£21) per ha. Larval root feeding is the primary source of damage, reducing nutrient uptake (Gavloski *et al*., 1992) leading to stunted plants. Adult feeding on maize pollen and cutting of the silks reduces pollination and contributes to lower yields. When considering grain yield, adults feeding alone on kernels, at densities of up to 20 adults per ear, do not cause significant yield reduction and moderate levels of silk clipping can be tolerated (Capinera *et al*., 1986). In the USA, Chiang *et al*., (1980) artificially infested field plots of maize with WCR eggs at the time of sowing. Yield losses ranged from 2 to 50%. Only at very high egg densities (2,400 eggs per plant) was there significant yield loss. In 2003 the USDA approved rootworm resistant maize. It is too early to predict the impact this will have on control, although, if accepted by import stakeholders, it could be a significant improvement giving systemic protection for a pest that is otherwise difficult to target by pesticide application.

Evidence from European countries suggests that there is a time lag of a number of years between the first finding of WCR and reports of economic damage[11] since it takes a number of years of growing continuous maize in a field before populations of WCR build up to densities sufficient to cause economic damage. WCR was first found in Europe in Yugoslavia (Serbia) in July 1992. Damage was reported as "severe" four years later (1996) although the damage was not quantified. In Yugoslavia, untreated WCR plots can suffer 40% yield losses. Root damage makes a maize crop more susceptible to lodging. When root damage coincides with a particularly wet year, lodging may occur in 48% of the crop. In a dry year, 20% of the crop may lodge (Kersei *et al*. 2002). In Croatian trials, Brmez *et al*. (2006) showed that there was no statistical correlation between grain yield and the amount of lodging but there was a positive relationship between the amount of root damage and plant lodging.

WCR was first detected in Hungary in 1995, and the first economic damage was reported six years later (2001). A survey of root damage was conducted in 919 fields covering 40,621 ha in Hungary during 2002. Larval damage was observed

[11] The time lag before any damage is seen seems to be widely accepted as at least 5 years after introduction into continuous maize (Cheek, 2003).

on 7,488 ha (18% of the survey area) and root damage reached an economic level on 5,381 ha (13% of the survey area), and plant lodging was observed in several fields (EPPO, 2003). WCR was first observed in Croatia in 1995 and heavy damage was observed for the first time in the eastern part of Croatia seven years later in 2002 (EPPO, 2003). In Romania, WCR was first reported in 1996. Some economic damage was sporadically observed in 2 out of 14 counties infested during 2002. During 1999, in counties of Yugoslavia where damage occurred, the mean yield of maize was reduced by an estimated 30% (EPPO, 2000a). Similarly Sivcev & Tomasev (2002) reported corn yield loss of between 1% and 70% in Yugolsavia although typically most fields suffered an estimated 30% loss in yield.

WCR has been found in Bosnia & Herzegovina (1996), Bulgaria (1998), Slovakia, Switzerland (2000), Ukraine (2001), Austria and France (2002) and Belgium, the Netherlands and UK (2003) but no economic damage has yet been reported in any of these countries (EPPO, 2003).

In Europe, where WCR damage makes it uneconomic to grow continuous maize, farmers are now switching to growing maize in rotation. This controls WCR populations, allowing maize to be grown in alternate years but reduces the farmers income since the substitute crops grown are not so valuable.

3.2 Potential impact in the UK

In continuous maize grown in Continental Europe, it takes between 4 and 7 years, though typically 5 years, for WCR populations to reach densities where economic losses are incurred (Cheek, 2004). When Sivcev & Tomasev (2002) assessed yield losses in southern Europe, losses ranged from 1% to 70% although typically most fields suffered an estimated 30% loss. In northern Continental Europe, Schaafsma *et al.* (2002) estimated a possible yield loss of 10% for German climatic and growing conditions whilst Dutch researchers considered yield losses in the Netherlands would be in the range of 6.5% to 13% if maize was left untreated. Yield losses for untreated fields in the north-eastern part of the USA have been assessed as 6.5% (Calvin *et al.*, 2001).

The present analysis assumes yield losses of between 5% and 10% would be seen in England & Wales in continuous maize 5 years after first infested. In a Maize Growers' Association (MGA) survey conducted in around 1998, 80% of maize was grown in rotation, 20% was continuous maize. The ratio is probably much the same today (S. Draper, pers. comm.). Whilst it is recognised that maize prices can range from £250-£800/ha, according to potential yield and local market conditions, £425-£525 would be more typical (Nix, 2006). The mid-point of £475 was used in the analysis.

The present value of future impacts

Due to the time value of money, the value of impacts occurring in the future should be discounted to show the present day equivalent value. The Treasury discount rate (3.5%) has been used to determine the present value of future impacts. Tables A5.2 to A5.4 shows the present value of mean annual losses over the next 20 years. It is based on 10,000 iterations of the simulation model that estimated the area occupied using three rates of spread.

Table A5.2: Mean annual losses to maize based on moderate spread of WCR

Year	1. Area of continuous maize where impacts occur (ha)	2. Discount factor	Present value of 5% yield loss (£'000) (1. x £475 x 5% X 2.)	Present value of 10% yield loss (£'000) (1. x £475 x 10% x 2.)
0	0	1.00	0.0	0.0
1	0	0.97	0.0	0.0
2	0	0.94	0.0	0.0
3	0	0.90	0.0	0.0
4	0	0.87	0.0	0.0
5	191	0.84	3.8	7.6
6	378	0.81	7.3	14.6
7	601	0.79	11.2	22.4
8	841	0.76	15.2	30.4
9	1,114	0.73	19.4	38.9
10	1,420	0.71	23.9	47.9
11	1,757	0.69	28.6	57.2
12	2,130	0.66	33.5	67.1
13	2,543	0.64	38.7	77.4
14	2,997	0.62	44.1	88.2
15	3,492	0.60	49.7	99.3
16	4,035	0.58	55.4	110.9
17	4,557	0.56	60.5	121.0
18	5,240	0.54	67.3	134.5
19	5,903	0.52	73.2	146.5
20	6,599	0.51	79.2	158.3
			611.1	1,222.2

Table A5.3: Mean annual losses to maize based on moderate-quick spread of WCR

Year	1. Area of continuous maize where impacts occur (ha)	2. Discount factor	Present value of 5% yield loss (£'000) (1. x £475 x 5% X 2.)	Present value of 10% yield loss (£'000) (1. x £475 x 10% x 2.)
0	0	1.00	0.0	0.0
1	0	0.97	0.0	0.0
2	0	0.94	0.0	0.0
3	0	0.90	0.0	0.0

4	0	0.87	0.0	0.0
5	386	0.84	7.7	15.4
6	839	0.81	16.2	32.4
7	1,423	0.79	26.6	53.2
8	2,131	0.76	38.5	76.9
9	3,002	0.73	52.4	104.7
10	4,045	0.71	68.2	136.4
11	5,245	0.69	85.4	170.9
12	6,620	0.66	104.2	208.5
13	8,130	0.64	123.7	247.5
14	9,713	0.62	142.9	285.7
15	11,345	0.60	161.3	322.6
16	12,980	0.58	178.3	356.7
17	14,522	0.56	192.9	385.7
18	15,790	0.54	202.7	405.4
19	16,695	0.52	207.2	414.3
20	17,263	0.51	207.1	414.1
		NPV	1,815.2	3,630.5

Table A5.4: Mean annual losses to maize based on quick spread of WCR

Year	1. Area of continuous maize where impacts occur (ha)	2. Discount factor	Present value of 5% yield loss (£'000) (1. x £475 x 5% X 2.)	Present value of 10% yield loss (£'000) (1. x £475 x 10% x 2.)
0	0	1.00	0.0	0.0
1	0	0.97	0.0	0.0
2	0	0.94	0.0	0.0
3	0	0.90	0.0	0.0
4	0	0.87	0.0	0.0
5	714	0.84	14.3	28.6
6	1,747	0.81	33.8	67.5
7	3,363	0.79	62.8	125.6
8	5,262	0.76	95.0	190.0
9	7,747	0.73	135.1	270.3
10	10,502	0.71	177.1	354.1
11	13,291	0.69	216.5	433.1
12	15,382	0.66	242.2	484.4
13	16,161	0.64	246.0	491.9
14	16,653	0.62	244.9	489.9
15	16,722	0.60	237.7	475.5
16	16,928	0.58	232.6	465.2
17	16,956	0.56	225.2	450.4
18	17,253	0.54	221.5	442.9
19	17,321	0.52	214.9	429.8
20	17,480	0.51	209.7	419.3
		NPV	2,809.3	5,618.5

Notes to explain Tables A5.2 to A5.4

Column 1: WCR spread is considered over the next 20 years. It is assumed that only 20% of the infested area is continuous maize and suffers economic losses 5 years after first infested.

Column 2: WCR spreads at three rates, described above as moderate (Table A5.2), moderate-quick (Table A5.3) and quick (Table A5.4). See text for details.

Column 3: To convert future yield losses to present values, the Treasury discount rate of 3.5% has been applied to show future costs in current terms. (The appropriate discount factor is shown in column 3)

Columns 4 and 5: The mean annual present value of 5% and 10% yield losses of maize worth £475 /ha are shown.

3.3 Sensitivity analysis

As the parameters used in the model change, the value of expected impacts also changes. The contribution of each parameter to the change can be examined through sensitivity analysis. Table A5.5 shows how the NPV of expected impacts varies as each value for a key parameter is halved (-50%) or doubled (+100%).

Table A5.5: Sensitivity analysis for key model parameters

Parameter description	change in parameter value	Resultant change in expected damage
Area occupied by WCR	- 50%	- 91.2%
	+ 100%	+ 105.6%
Spread rate	- 50%	- 66.3%
	+ 100%	+ 54.8%
Yield loss	- 50%	- 50.0%
	+ 100%	+ 100.0%
Value of maize	- 50%	- 50.0%
	+ 100%	+ 100.0%

There are linear relationships between maize value and NPV of impacts, and between yield loss and NPV of impacts, whilst area occupied has a greater influence than spread rate on NPV.

ANNEX 6

Impacts in Europe

The following are notes of examples of damage caused by WCR in Europe reported in the EPPO Reporting Service.

Table A6 i: *Diabrotica virgifera virgifera* spread and damage in Yugoslavia (Serbia) 1992 - 1997

Sources: Data for 1992 to 1995 is from EPPO (1996) for 1996 and 1997 is from EPPO (1998)

Year	Infested area (ha)	Area of crop damage	Level of attack
1992	0.5	0.5	"medium"
1993	110,000	6	80% of plants in the 6ha severely damaged and no harvest from this area (partly due to dry and warm weather)
1994	200,000	70	"moderate", although harvest obtained
1995	>200,000 ?	275	"low to medium"
1996	>200,000 ?	10,787	"severe"
1997	>200,000 ?	approx. 21,500	not as severe, due to favourable climate.

- In Yugoslavia only a restricted area of damage is seen and this is around Belgrade (in Serbia). In this area, yield losses are up to 20 % (but up to 80 % lodging has been seen locally) (EPPO, 1997).

- When WCR was first detected in Hungary in 1995, farmers did not think it a serious pest. Over the next few years WCR continued to spread without any significant visible damage. The first economic damage occurred in 2001. Economic damage occurred more widely in 2002 (Zseller & Szell, 2002) although this was not quantified.

- During 1998, approximately 11,000 km² within eight counties in southern Hungary were infested with WCR. In the Szeged area (Csongrád county) of Hungary, larval damage on roots was noted in 1997 and 1998. However, larval damage had not reached economic levels (EPPO, 1999).

- In Yugoslavia, the mean yield of maize was reduced by an estimated 30% (from 5 to 80% damage was observed) in counties where damage occurred (EPPO, 2000a)

Countries reporting economic damage

<u>Yugoslavia</u>

It is estimated that 72,250 km² are infested by *D. virgifera* and that economic damage occurred on 26,500 ha of maize fields during 2001 (67,550 km² infested in 2000 with damage on 50,000 ha in 2000). In areas where damage has been seen for several years, the level of damage is decreasing because maize is now rotated with other crops (Table A6 (ii)).

Hungary

D. virgifera was first found in Hungary in 1995, in the south of the country and has spread very significantly. Economic damage was observed in some areas in Bács-Kiskun and Csongrád counties during 2000. A survey of root damage was conducted in 919 fields covering 40,621 ha in Hungary during 2002. Larval damage was observed on 7,488 ha (18% of survey area) and root damage reached an economic level on 5,381 ha (13% of survey area), plant lodging was observed in several fields (EPPO, 2003).

Romania

The first find of *D. virgifera* was made in 1996 at Nadlac (Arad district bordering Hungary). In the following years, the pest spread towards the east. Larval damage was noted in 1999 in maize monoculture in some areas in the Caras-Severin county, and economic damage appeared in 2000 in these areas. Some economic damage was sporadically observed in two of 14 counties infested during 2002.

Croatia

WCR was first observed in Croatia in 1995 and heavy damage was observed for the first time in the eastern part of Croatia in 2002 (EPPO, 2003).

Table A6 ii Infested area and area of economic Western Corn Rootworm activity in Europe in 2001 (FAO/J. Kiss and C.R. Edwards based on data from Bertossa, Boriani, Festic, Igrc-Barcic, Ivanova, Omelyuta, Princzinger, Rosca, Sivicek, and Sivcev).

Country	Infested area (km2)	Area of economic adult activity (km2)	% infested area where economic damage occurs
Yugoslavia	72,250	26,500	36.7
Hungary	70,000	10,000	14.3
Romania	60,000	11,000	18.3
Croatia	15,500	4,000	25.8
Bosnia-Herzegovina	13,000	0	0.0
Bulgaria	7,000	0	0.0
Slovakia	6,300	0	0.0
Italy	4,000	0	0.0
Switzer-land	728	0	0.0
Ukraine*	1	0	0.0
Total	248,779	51,500	20.7

* estimate for the Ukraine.

ANNEX 7

BACKGROUND NOTES ON MAIZE GROWN IN THE UK

Which maize varieties are grown in the UK?

There are around 120 varieties of forage maize on the market in the UK and there were sales of seed of all of them in 2002. Information regarding which varieties are most widely grown is commercially sensitive and supplied to the British Society of Plant Breeders (BSPB) in strict confidence. However, the market is dominated by the early maturing varieties, especially maturity groups 7 and 8 (Dr. Penny Maplestone, BSPB pers. comm.). Table A7 lists forage maize varieties in maturity groups 7 and 8.

Table A7: The most commonly grown forage maize varieties in the UK

Variety name	Maturity class	Variety name	Maturity class
Advance	7	Avenir	8
Andante	7	Crescendo	8
Chelsea	7	Fabius	8
Chief	7	Hurrikan	8
Goldbar	7	Passat	8
Goldis	7	Pretti	8
Goldoli	7	Target	8
Goldsile	7	Vernal	8
Hudson	7		
Husar	7		
Renard	7		
Schumi	7		
Shetland	7		
Soldier	7		
Sonnet	7		

Note that NIAB does not provide a recommended list of maize varieties, but does provide descriptive lists.

When is maize grown?

Seed is sown in late March to mid April or even into May when soil temperatures should be a constant 8ºC at sowing depth. The crop flowers in late July in southern England and during August elsewhere. It is usually harvested in October or earlier in warmer years.

What crops are grown in rotation with maize?

In a Maize Growers' Association (MGA) survey conducted in around 1998, 80% of maize was in rotation, 20% was continuous maize. The ratio is probably much the same now (S. Draper, pers. comm.). On stock farms it is possible to plant grass, particularly Italian and/or perennial ryegrass after maize, which is grazed until late March then ploughed for sowing maize again in mid April. Thus, there is an alternation between maize and grass. If maize is grown on a mixed farm, a winter cereal, probably wheat, or oilseed rape can follow. However, as a fodder crop grown properly, maize is one of the most profitable crops to grow and can be continuously cropped without too many problems. Nevertheless, only 20% or so is grown continuously in the UK.

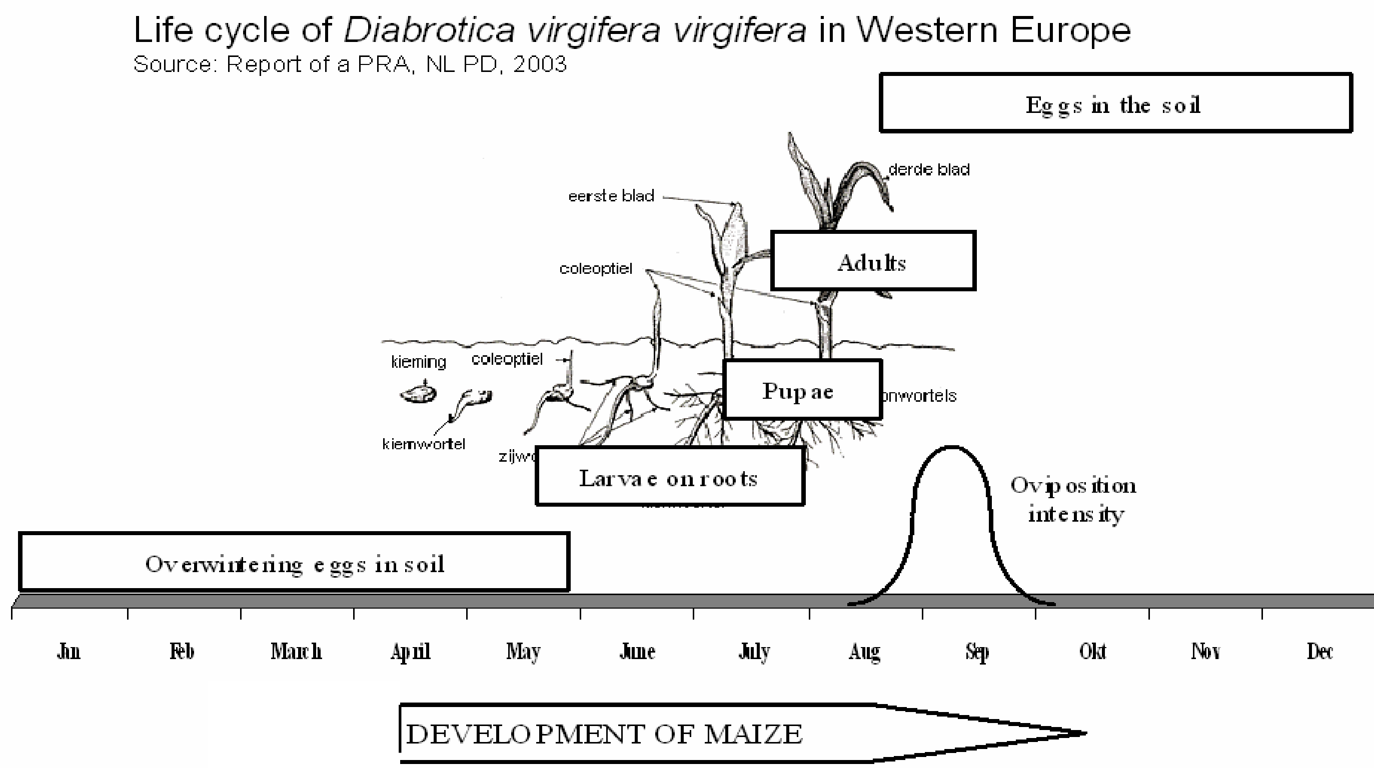
Maize yields
Satisfactory maize yields in Yugoslavia are around 5.5t/ha to 6.3t/ha. A very low yield of 1.8t/ha is possible. In France yields are higher, 35t/ha to >50t/ha, obtained using high yielding cultivars and intensive cropping measures (extracted from French PRA). In the UK, yields are around 25-30t/ha.

The increase of the area grown in the UK
During the 1990s, the area of maize grown in the UK dramatically increased (see Annex 1.) when varieties adapted to short day lengths, suitable for use in the UK were introduced. Maize is popular with dairy and beef farmers if they farm areas suitable to grow it. There is potential for a greater increase in the area of maize grown with climate change.

Game maize
The objective of game cover is to provide food and shelter for birds. They are often placed at strategic locations to link up existing habitat such as woodlands, and occasionally to provide bird runs. There is often little scope to change the location of the areas, however changing the composition to exclude maize is a possibility. Maize is the most common game cover plant, either in mixes or as single species blocks. It provides excellent cover and shelter due to its height and the cobs give a high quality food source from September through to January/February. No other crop provides this combination, however alternative mixes are available such as sorghum and millet (ADAS, 2004).

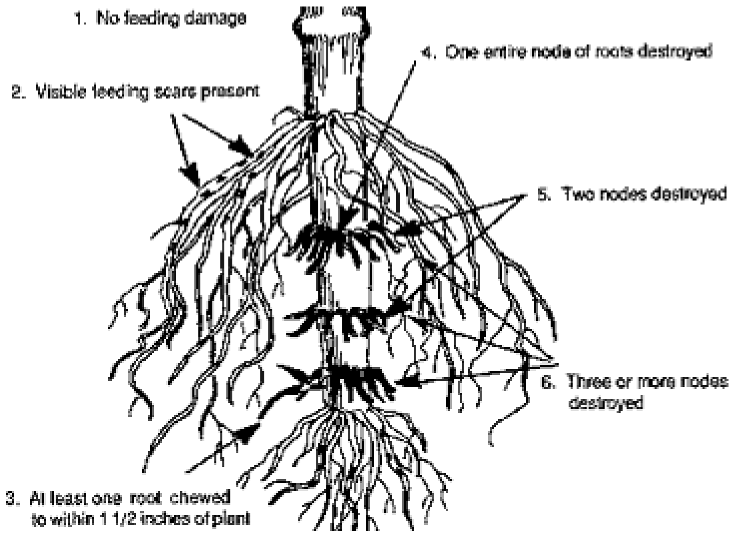
ANNEX 8

The life cycle of *Diabrotica virgifera virgifera* and key stages in maize development. (*Note that the phenology is based on conditions in Continental Europe, not UK*)



ANNEX 9

Description of the 1 to 6 root damage scale to assess *Diabrotica* spp. damage.



Acknowledgement
Illustration taken from University of Nebraska, Institute for Agriculture and Natural Resources (http://www.ianr.unl.edu/pubs/insects/g1108.HTM)

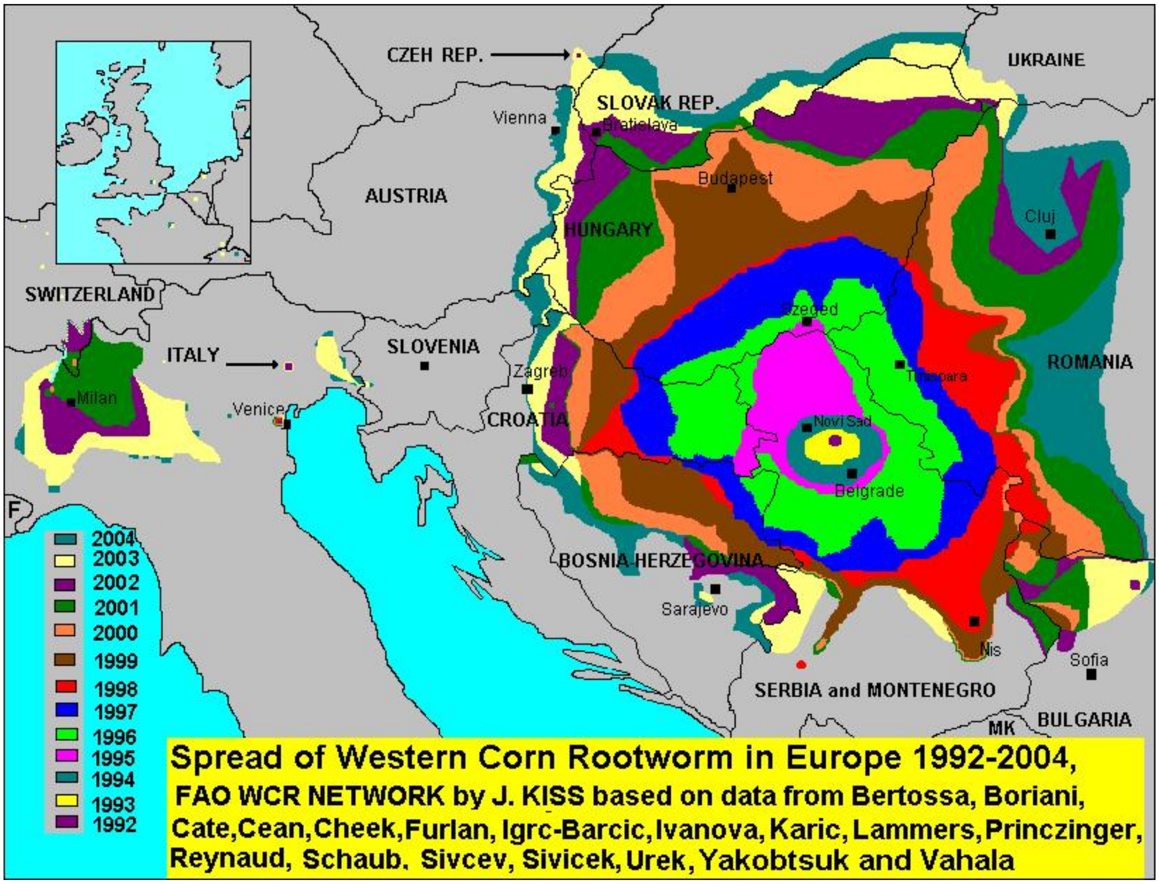
Rating	Description of root system
1	No noticeable feeding damage.
2	Feeding scars present but no root pruning.
3	At least one root pruned, but less than an entire node of roots pruned.
4	At least one full node of roots pruned but less than two full nodes.
5	At least two full nodes pruned, but less than three full nodes.
6	Three or more full nodes of roots pruned.

To qualify as a pruned root, the root must have been pruned to within 1 1/2" of the plant.

Rootworm larvae have chewing-type mouthparts and tunnel into and remove plant tissue while feeding. Damage may appear as superficial feeding scars (discolored injury points) or as "root pruning," which results from larvae chewing through the entire diameter of the root and tunneling into the root. The root rating scale is based on both types of feeding.

ANNEX 10

Fig A10: Annual spread of *Diabrotica virgifera virgifera* in Europe 1992 - 2004.



ANNEX 11

Maize area suitable for the development of WCR

The area of maize grown in England has changed markedly from 20 years ago, when approximately 20,000ha were grown annually. From the late 1990's to the present, the annual area of maize grown has fluctuated between 100,000ha and 120,000ha. This analysis assumes that the area of maize will continue to fluctuate between 100,000 and 120,000 ha until 2050.

Using climatic data from past years, and a thermal sum of 670 degree days (DD) above a threshold of 11ºC, the area of maize suitable for development of WCR in a hot year (1995) and a cool year (1996) has previously been determined (Baker *et al*., 2003; Table A11.1). The UK Climate Impact Programme (UKCIP) has predicted average climatic conditions in 2050 for a range of likely climate change scenarios.

To take a generally warmer, but varying, climate of the future into account, the mean area of maize suitable for establishment of WCR was estimated using Monte Carlo simulation. A number of assumptions were made:

1. the annual area suitable for WCR development would vary between the small area suitable in 1996 (cool) and the large area in 1995 (hot),
2. the annual area suitable was randomly selected from a distribution of areas between the small (1996) area and the large (1995) area with a target mean set between the UKCIP higher and lower estimates for 2050,
3. until 2050, maize continues to be grown in the same regions where it is currently grown,
4. until 2050, 48% of the 5km cells where the thermal sum exceeds 670DD grow maize (as in 1995),
5. until 2050, the area of maize in cells containing maize would remain at 2% (as in 1995).

Table A11.1: Maize area suitable for development of WCR under known conditions (1995, 1996) and predicted conditions (2050)

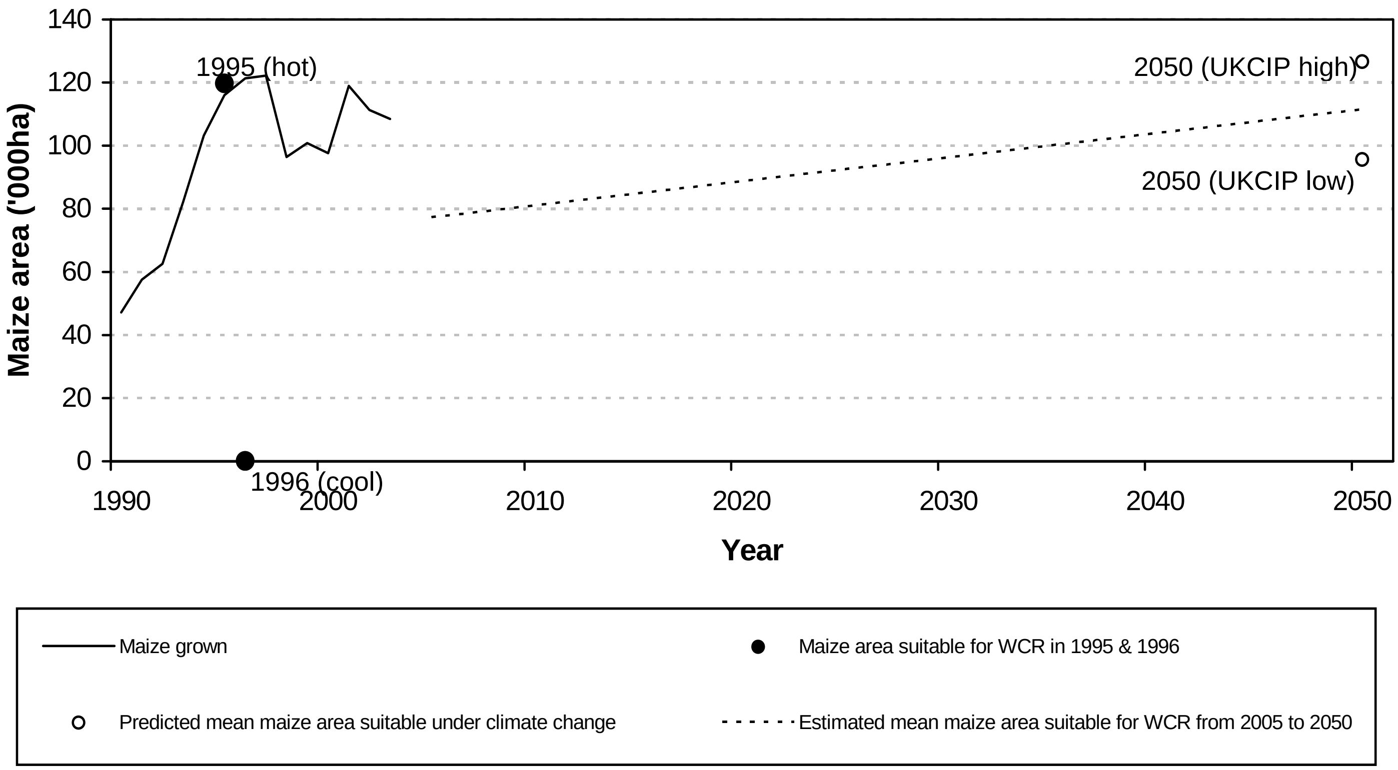
	1996	1995	2050 UKCIP low	2050 UKCIP High
No. of 5km cells	34	4,852	3,879	5,137
Cells with maize	3	2,333	1,865	2,470
% cells with maize	9%	48%	48%	48%
Convert cells to ha	7,500	5,832,500	4,662,875	6,175,093
% of suitable area with maize	1%	2%	2%	2%
Maize area suitable (to nearest 25ha)	75	119,725	95,600	126,600

Based on accumulated temperature under the UKCIP Low scenario, the typical maize area suitable for WCR establishment is just under 100,000 ha. Under the UKCIP High scenario, the maize area suitable for establishment is in excess of

120,000ha. (Table A11.1). Hence it is expected that by 2050, if maize is still grown to the same extent and in the same areas as now, the vast majority, if not all, of the maize in England will be grown in conditions typically suitable for the survival of WCR.

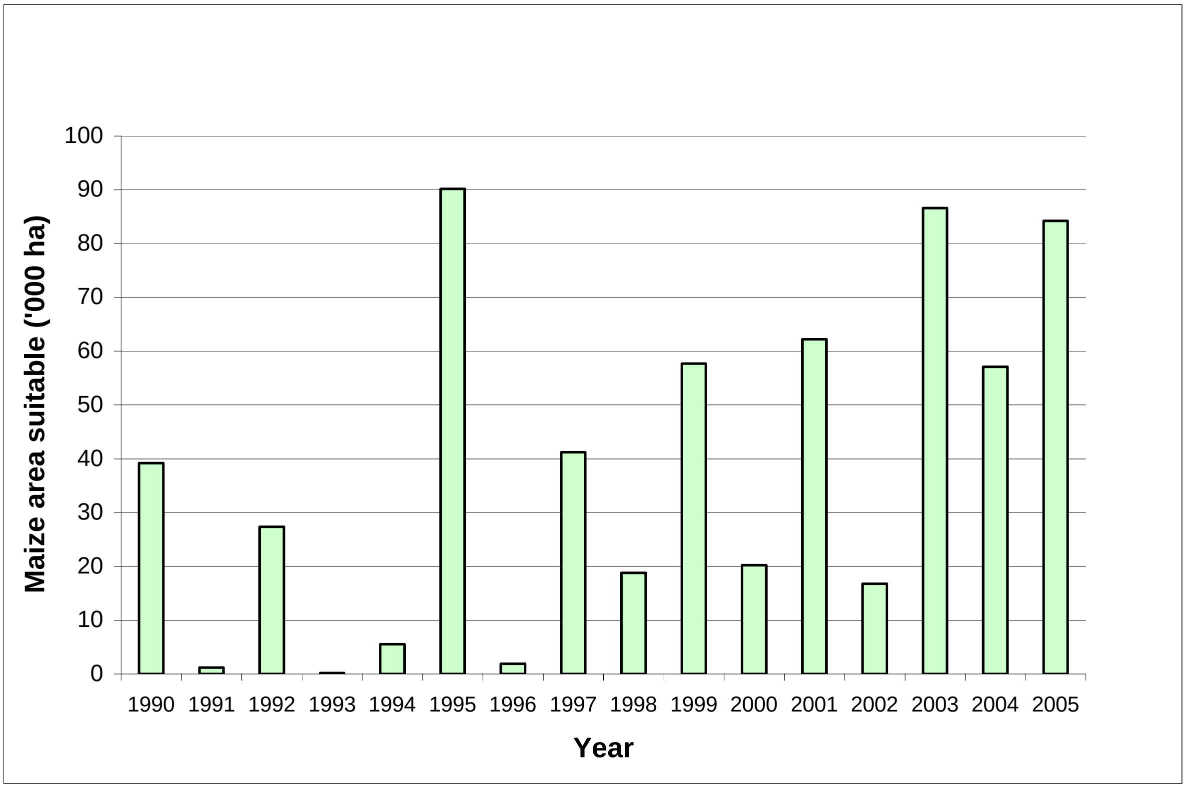
Figure A11.1 shows the area of maize grown in England from 1990. Also shown is the area that was suitable for development of WCR in 1995 and 1996 (closed circles). Based on data in Table A1, Figure A1 shows the expected area suitable for WCR development in 2050 under two alternative climate change scenarios (open circles). Results from the Monte-Carlo simulation, that account for annual variation in climate, shows the typical area of maize suitable for development of WCR as a dotted line gradually rising from a point between the area suitable in 1995 and 1996 to a point between the two options shown for 2050.

Figure A11.1: Maize area in England 1990 to 2003 (solid line). Dots indicate the maize area suitable for *Diabrotica* establishment under known UK climate conditions in 1995 (hot) and 1996 (cool) and two climates in 2050, based on UK CIP climate change scenarios.



ANNEX 12

Figure A12.1: Estimated maize area suitable for the development of western corn rootworm in England & Wales 1990-2005.



For each year, the estimated area was derived by,

1. Calculating the number of $5km^2$ grid cells where mean temperature accumulated to exceed 670 Degree Days above a threshold of 11°C.
2. Overlaying the grid cells where maize was known to be grown in 2000.
3. Converting the grid area to hectares.
4. Assuming maize occupied up to 2% of each grid (CSL unpublished data), the total grid area was multiplied by 0.02.

As noted in sections 15 of the PRA, 1995 was a hot year, 1996 was a cool year and 1997 more typical.

Caveat: The method used to estimate the area of maize suitable for WCR using data for 1995, 1996 and 1997, as described in Baker et al., (2003) was revised to estimate the areas for the years 1990 to 2005 (Figure A12.1). Compared to the original method, for hot years, the revised method estimated a smaller area of maize would be suitable for WCR but during cooler years the revised method estimated a greater area of maize would be suitable for WCR. The mean difference between methods for the years 1995, 1996 and 1997 was approximately +2,000 ha using the revised method.

REFERENCES

ADAS (2004) Economic assessment of the rotational measures within the EC control measures against Diabrotica virgifera in UK maize crops. Report by ADAS for Defra PHD, March 2004. 29pp.

Baca, F., Gosic-Dondo, S. & Veskovic, M. (2006) Effects of crop residues on plant lodging caused by larvae of *Diabrotica v. virgifera* and grain yield. Abstract of poster 002, IWGO 22nd Conference, Vienna, Austria, 5-8 November 2006.

Baker, C.R.B. (1980) Some problems in using meteorological data to forecast the timing of insect life cycles. *Bulletin OEPP/EPPO Bulletin*, **10**: 83-91.

Baker, R.H.A., Cannon, R.J.C. & MacLeod, A (2003) Predicting the potential distribution of alien pests in the UK under global climate change: Diabrotica virgifera virgifera. *Proceedings of the Britsh Crop Protection Conference - Crop Science and Technology,* Glasgow, November 10-12, 2003, 1201-1208.

Barcic, J.I. & Bazok, R. (2004) Current Status and results of the monitoring of western corn rootworms in 2003 in Croatia. *IWGO, 10th Diabrotica subgroup meeting, 14-16 January, Engelberg, Switzerland.*

Baufeld, P. (2003) Information about the dispersal rate with and without containment measures and the potential risk of WCR establishment in selected EU countries. In Vidal S. (2003) Threat to European maize production by the invasive quarantine pest Western Corn Rootworm (*Diabrotica virgifera virgifera*): a new sustainable crop management approach. EU Research Report QLRT-1999-01110.

Baufeld, P. & Enzian, S. (2001) Simulations model for spreading scenarios of western corn rootworm (*Diabrotica virgifera virgifera*) in case of Germany (http://www.infoland.at/clients/iwgo/)

Baufeld, P., Enzian, S. & Motte, G. (1996) Establishment potential of *Diabrotica virgifera* in Germany. *Bulletin OEPP/EPPO Bulletin,* **26**: 511-518.

Baufeld, P., Kiss, J., Unger, J-J., Hofmann, P., Jahn, G. & Terpo, I. (2006). Attraction of light sources and kerosene to adults of western corn rootworm (*Diabrotica v. virgifera*) Abstract of poster 004, IWGO 22nd Conference, Vienna, Austria, 5-8 November 2006.

Bernklau, E. J., Fromm, E. A., Bjostad, L. B. (2004) Disruption of host location of western corn rootworm larvae (Coleoptera: Chrysomelidae) with carbon dioxide. Journal of Economic Entomology. **97** (2), 330-339.

Bohn, M & Davis, G. (2006) Genomic evaluation of the defense response of maize against the western corn rootworm – how to use this information in breeding programs? Proceedings IWGO 22nd Conference, Vienna, Austria, 5-8 November 2006.

Branson, T. F. (1989) Survival of starved neonate larvae of *Diabrotica virgifera virgifera* LeConte (Coleoptera: Chrysomelidae). *Journal of the Kansas Entomological Society,* **62**: 521-523.

Branson, T.F. & Ortman, E.E. (1970) The host range of larvae of the Western corn roootworm: further studies. *Journal of Economic Entomology*, **63**: 800-803.

Breitenbach, S., Heimbach, U., Lauer, K. F. (2005) Field tests on the host range of the larvae of the western corn rootworm (Diabrotica virgifera virgifera LeConte 1868, Chrysomelidae, Coleoptera). Nachrichtenblatt des Deutschen Pflanzenschutzdienstes. **57**: (12), 241-244.

Breitenbach, S., Heimbach, U., Gloyna, K., Thieme, T. (2005). Possible host plants for larvae of western corn rootworm (*Diabrotica virgifera virgifera*). (Symposium Proceedings No.81) Plant protection and plant health in Europe: introduction and spread of invasive species, held at Humboldt University, Berlin, Germany, 9-11 June 2005. British Crop Protection Council, Alton, UK: 2005. 217-218.

Brezikova, M. & Zaruba, J. (2006). Spread of western corn rootworm (*Diabrotica v. virgifera*) in the Czech Republic. Abstract of poster 007, IWGO 22nd Conference, Vienna, Austria, 5-8 November 2006.

British Atmospheric Data Centre. (2003) http://badc.nerc.ac.uk/home/

Brmez, M., Ivezic, M., Raspudic, E. & Majic, I. (2006). Correlation between plant lodging caused by western corn rootworm and grain yield. Proceedings IWGO 22nd Conference, Vienna, Austria, 5-8 November 2006.

Brunt, A.A., Crabtree, K., Dallwitz, M.J., Gibbs, A.J., Watson, L. & Zurcher, E.J. (eds.) (1996 onwards). `Plant Viruses Online: Descriptions and Lists from the VIDE Database. Version: 20th August 1996.' URL http://biology.anu.edu.au/Groups/MES/vide/

Capinera, J.L., Epsky, N.D. & Thompson, D.C. (1986) Effects of adult western corn rootworm (Coleoptera: Chrysomelidae) ear feeding on irrigated field corn in Colorado. *Journal of Economic Entomology,* **79**: 1609-1612.

Cheek, S. (2003) Draft summary report of a visit to an International Symposium. The Ecology and Management of Western Corn Rootworm, 19-23rd January 2003, Goettingen, Germany. Unpublished CSL Report.

Chege, P.G., Clark, T. L., Hibbard, B. E. 2005. Alternate host phenology affects survivorship, growth, and development of western corn rootworm (Coleoptera: Chrysomelidae) larvae. Environmental Entomology. **34**: 6, 1441-1447.

Chiang, H.C., French, L.K. & Rasmussen, D.E. (1980) Quantitative relationship between western corn rootworm population and corn yield. *Journal of Economic Entomology,* **73**: 665-666.

Coats, S.A., Tollefson, J.J. & Mutchmor, J.A. (1986) Study of migratory flight in the Western Corn Rootworm (Coleoptera: Chrysomelidae). *Environmental Entomology*, **15**: 620-625

Davis, P.M., Brenes, N. & Allee, L.L. (1996) Temperature dependent models to predict regional differences in corn rootworm (Coleoptera: Chrysomelidae) phenology. *Environmental Entomology*, **25**: 767-775.

Defra (27 Sept., 2001) Seed Traders' Annual Return - Year ended 30 June 2001. National Statistics, 4pp. http://www.defra.gov.uk/esg/work_htm/notices/starpn.pdf

Defra (2003) http://farmstats.defra.gov.uk/cs/agricultural_atlas/map_select.asp

Dobrincic, R., IgrcBarcic J. & Edwards, C.R., (2003) The investigation of the relationship between western corn rootworm population level and corn yield - Croation experiences. (http://www.infoland.at/clients/iwgo/sub_meet_08/sub_meet_08a23.htm)

Elliott, N.C., Gustin, R.D. & Hanson, S.L. (1990) Influence of adult diet on the reproductive biology and survival of the western corn rootworm, *Diabrotica virgifera virgifera*. *Entomologia Experimentalis et Applicata*, **56**: 15-21.

EPPO (1996) Situation of *Diabrotica virgifera* in Serbia (YU). From International Workshop "Western Corn Rootworm in Europe 95", Gödöllö (HU), 1995-11-08. *EPPO Resporting Service* (1996/006).

EPPO (1997) Situation of *Diabrotica virgifera* in Central Europe. From Report of the 1st Meeting of the EPPO ad hoc Panel on *Diabrotica virgifera* held jointly with the 3rd international IWGO Workshop on *Diabrotica virgifera*, Zagreb, 1996-10-15/16. Plant Protection Service of Slovakia, 1997-01. *EPPO Reporting Service* (1997/033).

EPPO (1998a) *Diabrotica virgifera* trapped near Venezia airport (Italy) From: Osservatorio per le Malattie delle Piante di Verona, Servizio Fitosanitario Regionale del Veneto, 1998-08. *EPPO Reporting Service* (1998, 98/161).

EPPO (1998b) Present situation of *Diabrotica virgifera* in Central Europe. From abstracts of papers presented at the 2nd Meeting of the EPPO ad hoc Panel and 4th International IWGO Workshop on *Diabrotica virgifera virgifera* LeConte, Gödöllo (HU), 1997-10-28/30. *EPPO Reporting Service* (1998/001).

EPPO (1999) Details on the situation of several quarantine pests in Hungary in 1998. *EPPO Reporting Service* (1999/057).

EPPO (2000a) Situation of *Diabrotica virgifera* in the EPPO region. From papers presented at the 4th meeting of the EPPO ad hoc Panel on *Diabrotica virgifera* held jointly with the 6th International IWGO Workshop on *Diabrotica virgifera* in Paris, 1999-11-04/05. *EPPO Reporting Service* (2000/031).

EPPO (2000b) *Diabrotica virgifera* found in Albania. *EPPO Reporting Service* (2000/117).

EPPO (2001) Situation of *Diabrotica virgifera* in the EPPO region. From papers presented during the 5th Meeting of the EPPO ad hoc Panel on *D. virgifera* held jointly with the 7th International IWGO Workshop on *D. virgifera* in Stuttgart, DE, 2000-11-16/17. *EPPO Reporting Service* (2001/003).

EPPO (2002a) Situation of *Diabrotica virgifera* in the EPPO region. Papers presented at the 6th Meeting of the EPPO ad hoc Panel on *D. virgifera* held jointly with the 8th International IWGO Workshop on *D. virgifera* in Venezia, IT, 2000-10-29/30. *EPPO Reporting Service* (2002/001).

EPPO (2002b) First report of *Diabrotica virgifera virgifera* in France. *EPPO Reporting Service* 2002/139.

EPPO (2002c) PQR database (version 4.1). Paris, France: European and Mediterranean Plant Protection Organization.

EPPO (2003) The situation of *Diabrotica virgifera virgifera* (Coleoptera: Chrysomelidae) in Europe was reviewed during the 7th Meeting of the EPPO *ad hoc* Panel on *D. virgifera* held jointly with the 9th International IWGO Workshop on *D. virgifera* in Belgrade, 2002-11-03/05. *EPPO Reporting Service* (2003/001).

EPPO PQR (2005) EPPO Plant Quarantine Retrieval system, Version 4.5.

Fischer, F., Heimbach, U. & Schrader, S. (2006). Orientation of larvae of Diabrotica v. virgifera in different soil compositions and soil densities. Abstract of poster 012, IWGO 22nd Conference, Vienna, Austria, 5-8 November 2006.

Furlan, L., Canzi, S., Checchetto, F. & Delillo, I. The potential of the management of maize planting date in *Diabrotica v. virgifera* eradication-containment programmes. Abstract of poster 014, IWGO 22nd Conference, Vienna, Austria, 5-8 November 2006.

Furlan, L., Canzi, S., Di Bernado, A. & Edwards, C.R. (2006) The ineffectivness of insecticide seed coatings and planting-time soil insecticides as Diabrotica virgifera virgifera LeConte population suppressors. *Journal Of Applied Entomology*, **130** (9-10), 485-490.

Garthwaite, D.G., Thomas, M.R., Anderson, H.M. & Battersby, A. (2005). Pesticide Usage Survey Report 210, Grassland & Fodder Crops in Great Britain, CSL, Sand Hutton. 83pp.

Gavloski, J.E., Whitfield, G.H. & Ellis, C.R. (1992) Effect of larvae of western corn rootworm and of mechanical root pruning on sap flow and growth of corn. *Journal of Economic Entomology*, **85**: 1434-1441.

Gordon, D.T., Bradfute, O.E., Gingery, R.E., Nault, L.R. and Uyemoto, J.K. (2001) *Maize Chlorotic Mottle Virus*, Descriptions of plant viruses online, No. 284, AAB, http://www3.res.bbsrc.ac.uk/webdpv/web/fdpv.asp?dpvnum=284.

Grant, R.H. & Seevers, K.P. (1989) Local and long-range movement of adult western corn rootworm (Coleoptera: Chrysomelidae) as evidenced by washup along southern Lake Michigan shores. *Environmental Entomology*, **18** (2), 266-272.

Gray, M.E., Levine, E. & Oloumi-Sadeghi, H. (1988) Adaptation to crop rotation: western and northern corn rootworms respond uniquely to a cultural practice. *Recent Research Developments in Entomology*, **2**: 19-31.

Guillemaud, T. & Miller, N. (2006) Introduction routes of the western corn rootworm invading Europe. Proceedings IWGO 22nd Conference, Vienna, Austria, 5-8 November 2006.

Gupta, S.C., Larson, W.E. & Linden, D.R. (1983) Effect of tillage and surface residues on soil temperatures. I. Upper boundary temperature. *Soil Science Society of America Journal,* **47**: 1212-1218.

Guse, C.A. & Onstad, D.W. (2003) Modelling the dynamics of adaption of western corn rootworm to agricultural systems.. The Ecology and

Management of Western Corn Rootworm, International Symposium, 19-23rd January 2003, Goettingen, Germany.

Hibbard, B.E. (2006) Breeding for resistance to corn rootworm larval feeding: History, techniques, and the Missouri USDA-ARS program. Proceedings IWGO 22nd Conference, Vienna, Austria, 5-8 November 2006.

Hills, T.M., & Peters, D.C. (1971) A method of evaluating postplanting insecticide treatments for control of Western corn rootworm larvae. *Journal of Economic Entomology*, **64**: 764-765.

Hulme M; Jenkins G J; Lu X; Turnperry J R; Mitchell T D; Jones R G; Lowe J; Murphy J M; Hassell D; Boorman P; McDonald R; Hill S (2002). *Climate change scenarios for the United Kingdom: the UKCIP02 scientific report.* Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich UK.

Injac, M. & Krnjajic, A. (2000) Field trials on *Diabrotica virgifera* control at the initial foci of European occurrence. *Proceedings of the BCPC*, 937-942.

Isard, S.A., Spencer, J.L., Nasser, M.A. & Levine, E. (2000) Aerial movement of western corn rootworm (Coleoptera: Chrysomelidae): diel periodicity of flight activity in soybean fields. *Environmental Entomology*, **29**: 226-234.

Ivezic, M., Raspudic E., Brmez, M. & Majic, I. (2006). Results of 5-years investigations of corn hybrids tolerance to western corn rootworm larval feeding. Proceedings IWGO 22nd Conference, Vienna, Austria, 5-8 November 2006.

Jensen, S.G. (1985) Laboratory transmission of maize chlorotic mottle virus by three species of corn rootworm. *Plant Diseases*, **69**: 864-868.

Johnson, C.G. (1969) *Migration and Dispersal of Insects by Flight.* Methuen, London.

Keresi, T., Sekulic, R., Strbac, P & Latkovic, D. (2002) Influence of fertilization, hybrids and insecticides on western corn rootworm larval damage. *Proceedings of the 9th IWGO Diabrotica subgroup meeting and 8th EPPO ad hoc Panel, Belgrade 2002.*

Krysan, J.L. & Miller, T.A. (1986) Methods for the study of Diabrotica. Springer Verlag, New York, 260pp.

Krysan, J.L. Smith, R.F. Branson, T.F. & Guss, P.L. (1980) A new subspecies of *Diabrotica virgifera* (Coleoptera: Chrysomelidae): description, distribution, and sexual compatibility. *Annals of the Entomological Society of America*, **73**: 123-130

Levay, N., Szalai, M., Kiss, J., Baufeld, P. & Toepfer, S. (2006). Pilot studies to model population changes of western corn rootworm in dependence of regional share of continuous maize fields. Abstract of poster 020, IWGO 22nd Conference, Vienna, Austria, 5-8 November 2006.

Levine, E. & Oloumi-Sadeghi, H. (1991) Management of Diabroticite rootworms in corn. *Annual review of Entomology*, **36**: 229-255.

Levine, E., Oloumi-Sadeghi, H. & Ellis, C.R. (1992) Thermal requirements, hatching patterns, and prolonged diapause in western corn rootworm (Coleoptera: Chrysomelidae) eggs. *Journal of Economic Entomology*, **85**: 2425-2432.

Levine, E., Spencer, J.L., Isard, S.A., Onstad, D.W., Gray, M.E. 2002. Adaptation of the western corn rootworm to crop rotation: evolution of a new strain in response to a management practice. *American Entomologist* **48**, 94-107.

Li, H., Edwards, C.R. & Xue, D. (2006). Predicting the possiblity for establishment of the western corn rootworm, Diabrotica v. virgifera, in diffeent world regions: based on the CLIMEX model. Abstract of poster 016, IWGO 22nd Conference, Vienna, Austria, 5-8 November 2006.

MacLeod, A., Baker, R. H. A., Cheek, S., Cannon, R.J.C., Agallou, E. (2003) *Diabrotica virgifera virgifera* Pest Risk Analysis, CSL Plant Health Document, January 2003.

Meinke, L.J., Siegfried, B.D., Scharf, M.E., Wright, R.J., Chandler, L.D. & Parimi, S. (2001) Western Corn Rootworm Resistance To Insecticides -Development Of Resistance Management Strategies. Annual Report 2001 http://ott.arsusda.gov/projects/projects.htm?ACCN_NO=404357&fy=2001

Meloche, F., Filion, P., Tremblay, G. & LeSage, L. (2001) [Advance of *Diabrotica virgifera virgifera* (Coleoptera: Chrysomelidae) in corn fields in Quebec and sampling in soybean plants in Ottawa, Ontario] *Phytoprotection*, **82**: 35-38.

Metcalf, R.L. (1976) Organochlorine insecticides, survey, and prospects. In: Metcalf, R.L. & McKelvey, J.J. (Eds.) *The future for insecticides. Needs and prospects. Proceedings of a Rockefeller Foundation Conference Bellagio, Italy, April 22-27, 1974.* John Wiley, London. pp. 223-285.

Metcalf, R.L. (1983) Implications and prognosis of resistance to insecticides. In: Georghiou, G.P. & Saito, T. (eds.) *Pest Resistance to Pesticides* New York: Plenum Press, 703-733.

Meteorological Office (2006) http://www.metoffice.gov.uk/climate/uk/

Metcalf, R.L. & Metcalf, R.A. (1993) *Destructive & Useful Insects*, 5th Edn., McGraw-Hill, New York

Miller, N., Estoup, A., Toepfer, S., Bourguet, D., Lapchin, L., Derridj, S., Kim, K.S., Reynaud, P., Furlan, L. & Guillemaud, T. (2005). Multiple transatlantic introductions of the western corn rootworm. *Science*. 310: 992.

Modic, S., Knapi, M., Ergan, Z. & Urek, G. (2006) Spread and population dynamics of western corn rootworm, *Diabrotica v. virgifera* in Slovenia. Abstract of poster 022, IWGO 22nd Conference, Vienna, Austria, 5-8 November 2006.

Moellenbeck, D.J., Peters, M.L., Bing, J.W., Rouse, J.R., Higgins, L.S., Sims, L., Nevshemal, A., Marshall, L., Ellis, R.T., Bystrak, P.G., Lang, B.A., Stewart, J.L., Kouba K., Sondag, V., Gustafson V., Nour, K.,,Xu, D., Swenson, J., Zhang, J., Czapla, T., Schwab, G., Jayne, S., Stockhoff, B.A., Narva, K., Schnepf, H.E., Stelman, S.J., Poutre, C., Koziel, M. & Duck, N. (2001). Insecticidal proteins from *Bacillus thuringiensis* protect corn from corn rootworms. *Nature Biotechnology* 19, 668 - 672 (01 Jul 2001)

Moeser, J. & Vidal, S.(2003) Do alternative host plants in Europe enhance the invasion of the maize pest *Diabrotica virgifera virgifera* in Europe? (submitted to Environmental entomology): In, Vidal (2003) Threat to European maize production by the invasive quarantine pest Western Corn Rootworm (*Diabrotica virgifera virgifera*): a new sustainable crop management approach. EU Research Report QLRT-1999-01110.

Moeser, J. Vidal, S. (2004) Do alternative host plants enhance the invasion of the maize pest Diabrotica virgifera virgifera (Coleoptera: Chrysomelidae, Galerucinae) in Europe? *Environmental Entomology*. **33** (5), 1169-1177.

Moeser, J., Vidal, S. (2005). Nutritional resources used by the invasive maize pest Diabrotica virgifera virgifera in its new South-east-European distribution range. *Entomologia Experimentalis et Applicata*. **114** (1), 55-63.

Musick, G.J., Chiang, H.C., Luckmann, W.H., Mayo, Z.B. & Turpin, F.T. (1980) Impact of planting dates of field corn on beetle emergence and damage by the western and the northern corn rootworms in the corn belt. *Annals of the Entomological Society of America*, **73**: 207-215.

Naranjo, S.E. (1990) Comparative flight behavior of *Diabrotica virgifera virgifera* and *Diabrotica barberi* in the laboratory. *Entomologia Experimentalis et Applicata*, **55**: 79-90.

National Assembly for Wales (2001) Welsh Agricultural Statistics 2001 http://www.wales.gov.uk/keypubstatisticsforwales/content/publication/agriculture/2002/was2001/was2001-ch1.doc

National Climate Data Center (2003) http://www.ncdc.noaa.gov/oa/ncdc.html

New, M., Hulme, M. & Jones, P.D. (1999) Representing twentieth century space-time climate variability. Part 1: development of a 1961-90 mean monthly terrestrial climatology. *Journal of Climate*, **12**: 829-856.

Niblett, C.L. & Claflin, L.E. (1978) Corn lethal necrosis - a new virus disease of corn in Kansas. *Plant Disease Reporter*. **62**: 1, 15-19.

Nix, J. (2002) *The Farm Management Pocketbook*. 33rd Edn. (Sept. 2002) Wye.

North Central Soil Conservation Laboratory (2003). WeedCast 2.0 Technical Documentation. http://www.mrsars.usda.gov/morris/products/weedcast/help/tech.htm#soiltemp

Oerke, E.C., Dehne, H.W., Schonbeck, F. & Weber, A. (1994) *Crop production and crop protection - estimated losses in major food and cash crops*, Elsevier, 808pp.

Onstad, D.W., Spencer, J.L., Guse, C.A., Levine, E. & Isard, S.A. (2001) Modelling evolution of behavioral resistance by an insect to crop rotation. *Entomologia Experimentalis et Applicata*, **100**: 195-201.

Onstad, D.W., Crwoder, D.W., Isard, S.A., Levine, E., Spencer, J.L., O'Neal, M.E., Tarcliffe, S.T., Gray, M.E., Bledsoe, L.W., Di Fonzo, C.D., Eisley, J.B. and Edwards, C.R. (2003) Does landscape diversity slow the spread of rotation-resistant Western corn rootworm (Coleoptera: Chrysomelidae)? *Environmental Entomology*, **32** (5), 992-1001.

Preston, C.D., Pearman, D.A., Dines, T.D. 2002. New Atlas of the British & Irish Flora. Oxford University Press.

Prystupa, B., Ellis, C. R. & Teal, P. E. A. (1988) Attraction of adult *Diabrotica* (Coleoptera: Chrysomelidae) to corn silks and analysis of the host-finding response. *Journal of Chemical Ecology,* **14**: 635-651.

Reynaud, P. (1998) Risk assessment of *Diabrotica virgifera virgifera* Le Conte in France. *Pflanzenschutzberichte*, **57**: 46-51.

Reynaud, P. (2002) Mais, la chrysomele des racines *Diabrotica virgifera,* premier signalement en France [First occurrence in France of the western corn rootworm *Diabrotica virgifera* Leconte]. *Phytoma*, **555**, Dec 2002. 18-21. (in French).

Siegfried, B.D., Meinke, L.J., Scharf, M.E., Wright, R.J., Chandler, L.D., Parimi, S., Caprio, M. (2001) Organophosphate resistance in western corn rootworms (*Diabrotica virgifera virgifera*): a model of development of future resistance management strategies? Resistance 2001 Meeting the Challenge, IARC Rothamsted, UK. 23-26 Sept. 2001.

Sivcev, I., Stankovic, S., Allara M., Fredrix, M., Jiggins, J & Cvrkovic, T. (2006) Western corn rootworm (WCR) management by crop rotation on risk assessed corn fields. Proceedings IWGO 22nd Conference, Vienna, Austria, 5-8 November 2006.

Soffe, R.J. (1995) *The Agricultural Notebook*, 19th Edition, Blackwell, Oxford.

Stavisky, J. & Davis, P.M. (1997) The effects of corn maturity class on western corn rootworm (Coleoptera: Chrysomelidae) phenology. *Journal of the Kansas Entomological Society*, **70**: 261-271

Stamm, D.E., Mayo, Z.B., Campbell, J.B., Witkowski, J.F., Andersen, L.W. & Kozub, R (1985) Western corn rootworm (Coleoptera: Chrysomelidae) beetle counts as a means of making larval control recommendations in Nebraska. *Journal of Economic Entomology,* **78**: 794-798.

Tutin, T.G., Heywood, V.H., Burges, N.A., Moore, D.M., Valentine, D.H., Walters, S.M. & Webb, D.A. (1980) *Flora Europaea,* Volume 5, Cambridge University Press.

UK Meteorological Office (2003) http://www.metoffice.com/research/hadleycentre/obsdata/ukcip/index.html

Uyemoto, J. K. Bockelman, D. L. Claflin, L. E. (1980) Severe outbreak of corn lethal necrosis disease in Kansas. *Plant Disease* (*formerly Plant Disease Reporter*). **64**: 1, 99-100.

Vidal S. (2003) Threat to European maize production by the invasive quarantine pest Western Corn Rootworm (*Diabrotica virgifera virgifera*): a new sustainable crop management approach. EU Research Report QLRT-1999-01110.

Witkowski, J.F., Owens, J.C. & Tollefson, J.J. (1975) Diel activity and vertical flight distribution of adult western corn rootworms in Iowa cornfields. *Journal of Economic Entomology*, **68**: 351-352.

Zseller, I.H. & Szell, E. (2002) Estimation of yield in correlation with the western corn rootworm larval damage and weather conditions. *Proceedings of the 9th IWGO Diabrotica subgroup meeting and 8th EPPO ad hoc Panel, Belgrade 2002.*