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Key pests and options to reduce pesticides in eleven European regions

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Glossary

Definitions in the context of this report:

Alternative pest control methods: Pest control methods not relying on chemical pesticides.

Important pest species: potentially causing reductions in yield quantity or quality in the absence of control measures

Integrated pest management (IPM): Concept of using different techniques in combination to control pests efficiently, with least adverse effects on the environment and most specificity to the particular pest. A set of decision rules is used to identify the need for and selection of appropriate control actions that provide economic benefits to growers and society while keeping chemical control of pests to a minimum.

Pesticides: Chemical and non chemical plant protection products applied in the form of soil granules, on-plant microgranules, seed treatments or spray formulations in maize growing against arthropod pest (insecticides, acaricides), fungal diseases (fungicides), and weeds (herbicides).

Pests: Herbivorous arthropods, fungal diseases and weeds that have the potential to cause economically significant damage to the maize crop.

Summary

Maize is one of the most important crops in the European Union (EU). With the increased application of chemical pesticides, farmers have been able to control pests easily, reliably and inexpensively, but adverse effects on the environment and human health raised concerns. Political efforts are made in the EU to reduce pesticides and to increase the implementation of integrated pest management (IPM). Within the EU project ENDURE, research priorities on pesticide reduction are defined. Using maize as a case study, we identified the most serious weeds, arthropod pests, and fungal diseases as well as the classes and amounts of pesticides applied in 11 representative maize growing regions in the EU. Data were collected from different databases, publications and expert estimates. Maize production was dominated by silage maize in the North and grain production in central Europe and the South. Crop rotation ranged from continuous growing of maize over several years to well plan rotation systems. There are several species of weeds, arthropod pests and fungal diseases that cause economic losses in most regions, even though differences exist between northern countries and central and southern Europe. Several weed and arthropod pest species cause increasing problems, illustrating that the goal of reducing chemical pesticide applications is challenging. Pesticides could potentially be reduced by the choice of varieties (including genetically modified hybrids), cultural methods including crop rotation, use of biological control, the optimization of application techniques of chemicals, and the development of more specific treatments. However, restrictions in availability, organization, and training and knowledge of farmers need to be overcome before environmentally friendly pest control strategies can replace chemical pesticides in an economically competitive way. The complex of several problems that need to be tackled simultaneously and the link between different control methods demonstrates the need for IPM approaches, where pest control is seen in the context of the cropping system and on a regional scale. Multicriteria assessments and decision support systems in combination with monitoring programs may help to develop region-specific and sustainable strategies.

Teams involved:

	Institute	**Country**
ACTA	Association de coordination technique agricole	France
AGROS	Agroscope Research Station ART	Switzerland
AU	University of Aarhus	Denmark
CNR	Consiglio Nazionale delle Ricerche	Italy
DAAS	Danish Agricultural Advisory Service	Denmark
IBMA	International Biocontrol Manufacturers Association	
IHAR	Instytut Hodowli i Aklimatyzacji Roslin	Poland
JKI	Julius Kühn-Institut (former BBA)	Germany
SSSUP	Scuola Superiore Sant'Anna (Pisa)	Italy
SZIE	Szent István University	Hungary
UdL	Universitat de Lleida	Spain
WUR/PPO	Wageningen University and Research Centre/ Praktijkonderzoek Plant & Omgeving (Applied Plant Research)	Netherlands

The Maize Case Study was running 16 month. The Kick- off meeting was held on 1-2 April 2008 at Agroscope ART Zurich; the Final Report was delivered end of July 2009.

Geographical areas covered:

Totally are eight countries with eleven regions included in this study:

- Spain: Ebro Valley
- Italy: Po Valley
- Hungary: Tolna and Békés County
- Poland: Southwest
- Germany: Southwest
- Denmark: Whole country
- Netherlands: Whole country
- France: Normandie, Grand-Ouest and Southwest

Degree of validation and operability of findings:

The results presented in chapters 3-8 are in the form of a scientific paper, ready to be submitted to an international journal for reviewing. Initially collected data were evaluated on a workshop and additional knowledge from invited experts was gathered. Subsequently, data were verified, harmonized and completed by all authors. The paper will be approved by all co-authors. It has also been sent to Endure on M31 for approval before submitting to the foreseen journal.

The results in chapter 9 are expert opinions that had been discussed at the workshop on 2-3 April 09 at Agroscope Zurich. This information is therefore a valuable bottom-line to be used by the Maize System Case Study (RA2.6b MBCS).

Three leaflets will be produced with ready to use information by this activity (Chapter 10). The drafts are sent to maize case study members and other selected scientists with expertise in the respective field. Their opinions and suggestions are incorporated in the leaflet before publication. If as many experts as possible agree with the content, this ensures that the leaflets will be distributed widely and by many people. The first leaflet (Corn borer control) is completed and in the stage of publication with A. Lewer. Leaflets two (Fungal diseases) and three (Corn rootworm control) are available as drafts.

Introduction

Knowledge of the current status of pests and pesticide use in different maize growing regions is a prerequisite for European research on the development of advanced cropping systems with less reliance on pesticides. A summary of such basic information is highly demanded since data for Europe are currently only available on a very general level from official databases (e.g. Eurostat) and national databases that are difficult to access. Most knowledge on the current status of pests is distributed regionally among crop protection experts. Together with such experts from several study regions across Europe, we designed a survey questionnaire that was completed by those experts from each region separately (available at the ENDURE website, ENDURE tools – Questionnaire/Survey list – Survey Questionnaire Maize Case Study). In addition to basic figures describing the maize cropping system, the significance, occurrence and development of most important pest species was rated. In order to harmonise the ratings, the preliminary results were discussed at a workshop where all experts were invited. The revised results were than sent to the experts once more for final adjustments and double check. This procedure of data collection and verification resulted in a robust dataset ready for publication in a scientific journal.

The preliminary results of this activity were presented at the 23rd conference of the Global International Working Group on *Ostrinia* and Other Maize Pests (IWGO) of the International Organisation for Biological and Integrated Control of Noxious Animals and Plants (IOBC), 5-8 April 09, Munich, Germany (available on the ENDURE workspace, ENDURE activities, RA3.1). Furthermore, data were presented at meetings with other Endure partners who will be responsible for the follow up sub-activity RA2.6b (Maize Based Cropping Systems, MBCS).

Alternative crop protection methods to reduce pesticide use are available, but rarely used in agricultural practice. Therefore, we decided to investigate potential options in order to understand the restrictions that need to be overcome. Each participating country was asked to suggest options and restrictions to reduce pesticide applications in the context of the results from the survey questionnaire. The suggestions from the different experts were then discussed at the workshop. In addition, specific knowledge was presented by invited specialists, such as integrated weed management, biocontrol of corn borer by *Trichogramma*, biocontrol of corn rootworm (*Diabrotica*) by entomopathogenic nematodes (EPN), forecast and warning systems, selecting non-target species for regulatory risk assessment of Bt-maize, management of *Fusarium* and mycotoxin problems, life cycle assessment and economic data.

This report covers the described activities as follows:
The results of the survey questionnaire maize (DR3.7) represent one part of the scientific paper in chapter 3 to 7: An overview of the situation of weeds, arthropod pests and fungal diseases in Europe. Furthermore, options to reduce herbicides, insecticides and fungicides by using alternative control methods are presented together with major constraints of those alternatives (DR1.18). Conclusions are presented in chapter 8. Based on those results and on the knowledge compilation in chapter 9 we extracted ready to use information, addressing extension services, advisers and maize growers in chapter 10 in the form of 3 leaflets (DR1.19). Finally the used data sources and cited references are presented.

Disseminations of results:

- One scientific paper in an international journal.
- Three Endure leaflets addressing extension services, advisors and farmers
- 13 presentations on knowledge for advanced pest control are available on the Endure website (ENDURE activities – Case studies: Maize – Knowledge compilation for

advanced pest control). Later these documents will be available also by the Endure Information Centre (EIC).
- The outcome of this activity will be implemented for the development of pest control strategies within the IWGO (www.iwgo.org)

This final report comprises the results of the whole Maize Case Study (16 month). We hope that our work opens perspectives to serve particularly the follow-up Endure sub-activity "Maize System Case study" (MBCS, RA2.6b), as evident from the first meetings of this group. Furthermore, we believe that the planned publication will contribute to knowledge for science and practice towards more sustainable maize cropping in Europe.

1. State of the art

Maize is one of the most important crops worldwide with an annual cultivation area of more than 150 million hectares and an annual harvest of almost 800 million tonnes of grain (FAOSTAT, 2007). Within the European Union, maize is grown in almost all countries. In the 27 EU member states, the cropping area in 2007 reached 8.3 million hectares for grain maize and 5.0 million hectares for silage maize. The annual total yield was 48.5 million tonnes of grain. The largest maize producers are France, Romania, Germany, Hungary and Italy, where maize is grown on more than 1 million hectares each (EUROSTAT, 2007).

Yield and quality of maize (as for other crops) are at risk by animal pests, weeds, and pathogens (Oerke, 2006). About 50 years ago, agricultural production has been increased dramatically when high yielding varieties and synthetic fertilizers became available. In addition, the extensive use of chemical pesticides, which allowed farmers a better pest control, contributed substantially to the so-called "green revolution" (Eichers, 1981; Kogan, 1998; Newsom, 1980). However, the increased use of pesticides resulted in adverse effects on human and animals health, environmental pollution (water and soil), and side effects on beneficial organisms including pollinators, decomposers and natural enemies (Pimentel, 2005; Metcalf, 1986). More intensive cultivation practices and increased input of herbicides with broader spectra of activity, have furthermore contributed to the impoverishment of the flora and indirectly of the weed-associated fauna in agricultural landscapes (Marshall et al., 2003). Chemical pesticides often lack sustainability, since their improper use promotes the development of pest resistance (Kogan, 1998; Pimentel, 2005; Metcalf, 1986). For example, more than 300 weed biotypes with resistance to herbicides are known, most of them from Europe and North America (Heap, 2009; De Prado & Franco, 2004).

Integrated production is a farming system that produces high quality food and other products by using natural resources and regulating mechanisms to replace polluting inputs and to secure sustainable farming (Boller et al., 2004). Within this context, integrated pest management (IPM) promotes the use of different techniques in combination to control pests efficiently, with an emphasis on methods that are least injurious to the environment and most specific to the particular pest. A set of decision rules is used to identify the need for and selection of appropriate control actions that provide economic benefits to farmers and society while keeping chemical control of pests to a minimum (Huffaker & Smith, 1980; Kogan 1986, 1998; El Titi, 1992; Boller et al., 2004). National and EU legislative directives have been imposed to limit pesticides and thus their negative impacts on the environment and human health (Lotz et al. 2002; Thonke 1991; Ackermann, 2005). One of the most prominent examples for Europe is the herbicide atrazine, which has been banned in Germany and Italy already in 1991 and in the remaining EU member states in 2005 (Ackermann, 2005). However, different initiatives from scientific organizations and policy makers in the European Union have the aim of further reducing pesticides and of implementing IPM in modern agriculture (Boller et al., 1997; Freier & Boller, 2009).

Since 2007, the ENDURE network of excellence, comprising more than 300 European researchers, is committed to define research priorities on pesticide reduction (www.endure-network.eu). To achieve this goal on a European level, a better understanding of the current status of pests and pesticide use, cultivation practices, and major driving forces is needed. For a general overview, the availability of comparable data, however, is a major difficulty. Data collected from national or regional institutions are often difficult to access and methods of data collection vary. In addition, knowledge and experience from agricultural practice is often with experts only and not publicly available. Using the maize crop as a case study, our aims were (1) to give an overview of European maize cultivation practices, (2) to identify the status and development of most serious arthropod pest, weed and disease problems in maize, (3) to compile data the classes and amounts of pesticides used, and (4) to discuss currently available options for pesticide reduction, potential long-term solutions, as well as their major restrictions.

This kind of evaluation of key pest and pesticide use is unique. Since the core part of this report is equivalent with a scientific paper which will be published in an international journal, the results of the Endure Maize Case Study will be disseminated to a wide scientific audience.

2. Material and methods

Data were collected from 11 growing regions representing maize production all over Europe (Fig. 1). Denmark and the Netherlands represented northern Europe, Southwest Poland and 2 Hungarian counties (Békés and Tolna) represent central Europe, Italy (Po Valley region) and Spain (Ebro Valley region) the Mediterranean region, and France with the regions Southwest, Grand-Ouest and Normandie represent Western Europe. In addition, Southwest Germany is also included in the study.

The size of the maize production areas in the focus regions ranged from 50’000 ha in the Tolna region (Hungary) to 1.2 million ha in the Po Valley (Italy) (Fig. 1).

From May 2008, the authors of this paper, who are experts representing institutions of major maize producing countries, compiled data on maize cultivation characteristics, arthropod pests, weeds, and fungal pathogens. Published data, data from public and internal statistics as well as expert estimates were included. Data derived mainly from the growing season 2007, but previous years were considered if no other data were available. For further details on data sources, see Supplemental Information. In a workshop held in April 2008, data were evaluated, additional knowledge from invited experts was gathered, and options and restrictions for pesticide reductions were discussed. Subsequently, data were verified, harmonized and completed by all authors.

The procedure used in the Maize Case Study to combine comparable data and information on the current status of key pests of different countries could be used also in future. It would also make sense to repeat such an evaluation periodically in the same regions in order to get a picture of the development.

3. Maize cropping systems in eleven European regions

Maize in the selected regions was produced mainly for silage or grain maize (Fig. 1). Seed and sweet maize production and maize production for agro-fuel or gas were below 15% in all regions, even though the latter is expected to increase. Climatic conditions (temperature and precipitation) are major factors influencing the type of maize production. From north to south and from oceanic to more continental regions, precipitation from April to October decreased and temperature increased. Consequently, silage maize was mainly produced in north-western European regions, while grain maize production dominated in central and southern regions (Fig. 1). The highest input of nitrogen fertilizers (organic and synthetic) was reported from the Ebro Valley (Spain, 350 kg/ha), followed by France, the Po Valley (Italy), and the Netherlands (180-230 kg/ha). Lowest nitrogen inputs occurred in Southwest Germany and Poland, where the amount of fertilizer was only 1/3 compared to the Ebro Valley (Fig. 1). Fertilizers were commonly applied in 1 or 2 fractions per year, in the Ebro Valley sometimes

also in 3 fractions. A limited area (less than 30%) of the total maize production area all over Europe was not ploughed (reduced tillage or no tillage, Fig. 1). Organic maize production was below 3% in all regions.
The percentage of maize rotated with other crops varied for the regions from 20 to 85% of the maize area. Highest percentages of rotation occurred in Békés region (Hungary) and Southwest Poland and lowest in Southwest France. The most common crop included in the rotation was wheat (or barley) in a 2-year cycle. However, a range of different rotations with 2-5 crops, including maize, wheat, alfalfa, sunflower, temporary grassland, soybean, beets, oilseed rape, rice, and potato has been practiced in Europe.

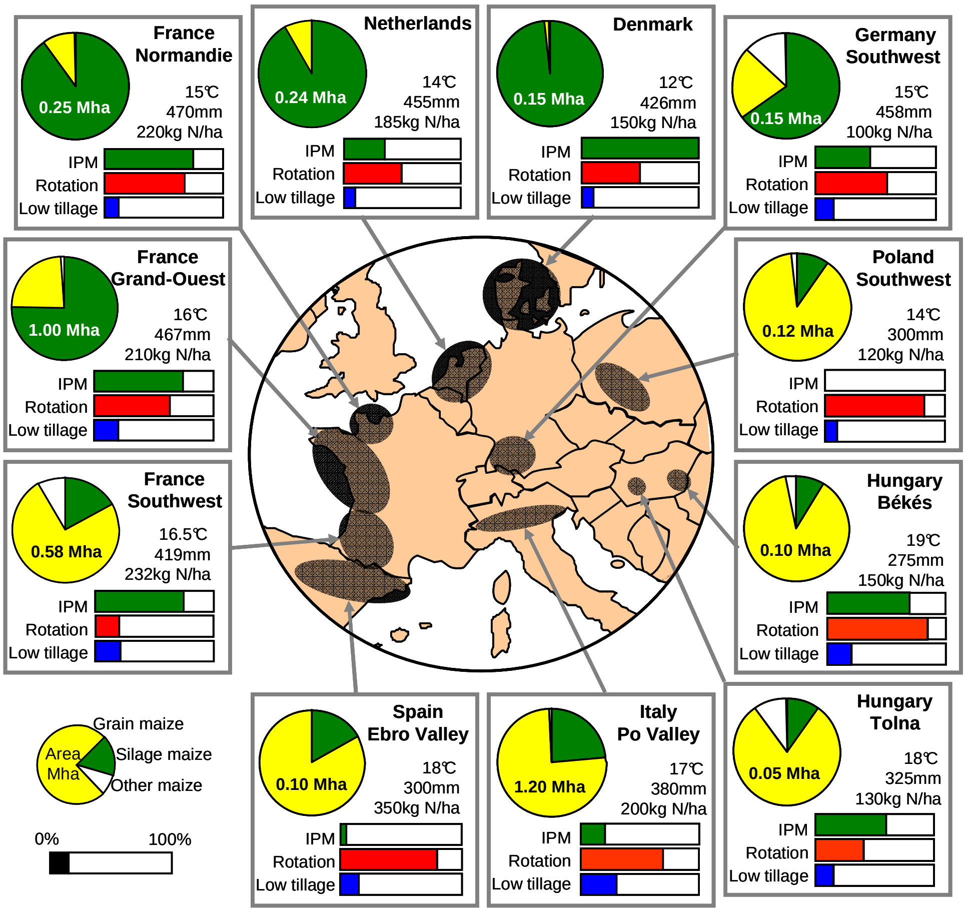


Fig. 1. Maize production characteristics in 11 regions in Europe. Pie diagrams: Maize production type: Silage (green), grain (yellow) and other (white); Numbers in diagrams: total maize area in the region (in million hectares); Numbers outside diagrams: Average temperature (℃) and precipitation (mm) from April to October and fertilizer (synthetic and organic) applied per year (kg nitrogen input per ha); Bar diagrams: Percentage of maize area under IPM (including organic), crop rotation (no maize after maize), low tillage (including no tillage) soil management versus ploughing. Full bars represent 100%.

IPM guidelines exist in all covered regions and the maize area, where those guidelines were applied, was highly variable. According to the definition by the International Organisation for Biological and Integrated Control of Noxious Animals and Pests (IOBC), one fundamental principle of IPM is that arable crops (including maize) should not be grown more than one year in two (Boller et al., 2004). However, Denmark reported to conduct 100% IPM, even though maize after maize was cultivated on 50% of the maize area (Fig. 1). More than 50% of the area in Hungary and France was reported to be cultivated under IPM (Fig. 1). For Hungary, the implementation of national integrated production guidelines similar to those of IOBC is linked to subsidies under agro-environmental programs (Kiss, 2008). All other regions applied IPM on less than half of their maize production area and no IPM was reported from Southwest Poland, even though crop rotation was very common. One reason for Poland is the fact that the guidelines have been issued only recently and have thus not been adopted by farmers yet. Those examples demonstrate that the definition of IPM by national or regional authorities can vary substantially. Harmonization of IPM principles within national guidelines (including labelling) is therefore recommended before IPM can be promoted and implemented on a European level.

4. Weeds

4.1. Situation of weeds in Europe

More than 50 weed taxa were mentioned as being important in European maize production. Important in the context of this report is defined as potentially causing reductions in yield quantity or quality in the absence of control measures. The most important monocotyledonous weeds are Poaceae such as *Echinochloa crus-galli* and *Setaria viridis* which cause problems in all European countries (Fig. 2).

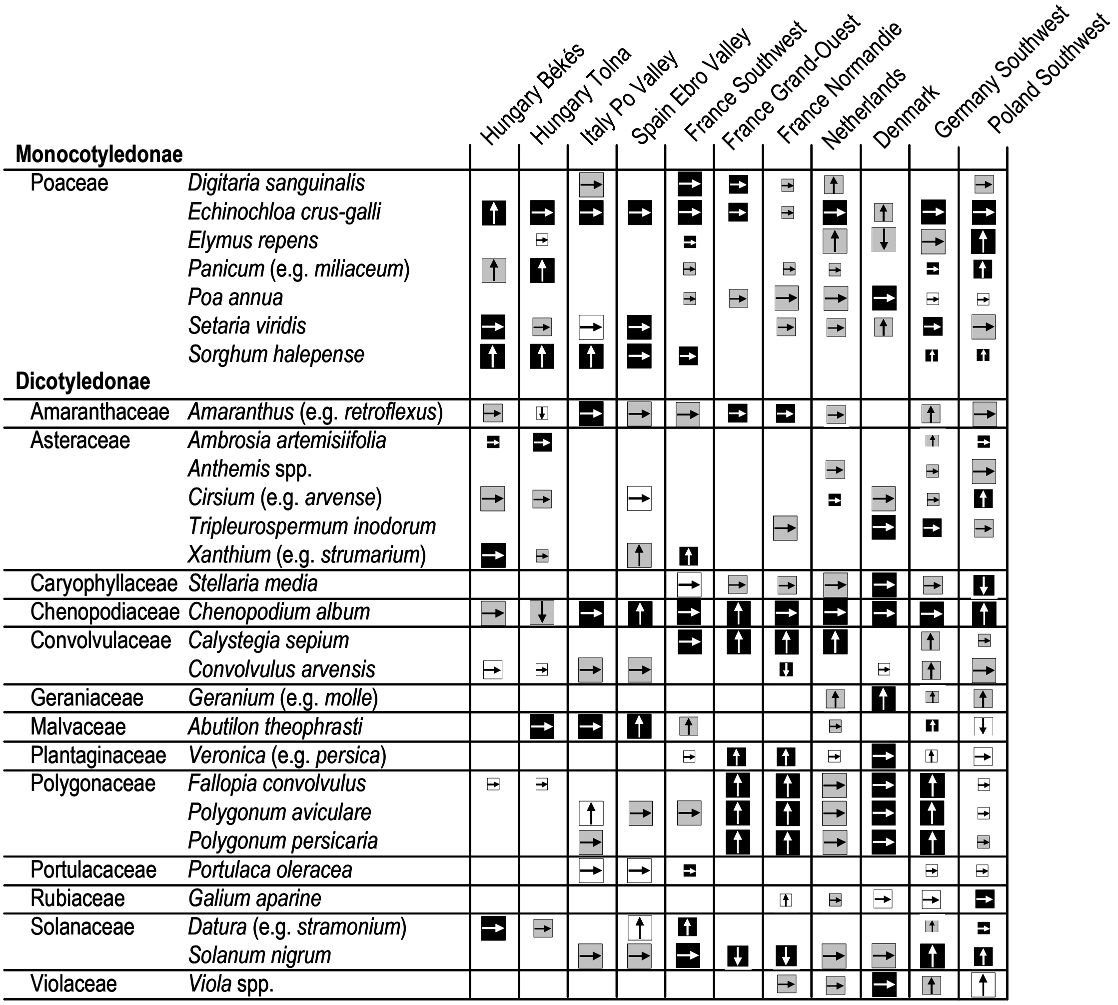


Fig. 2. Most important weeds in European maize production. Significance is represented by symbol colour: black = high, grey = medium, white = low. Occurrence is represented by symbol size: large = widespread and regularly, medium = widespread and occasionally, small = regionally and rare. The 5-year population development is represented by arrows: up = increasing, horizontal = stable, down = decreasing.

While *Sorghum halepense* is a major weed in central and southern regions, *Elymus repens* and *Poa annua* are important (even if less competitive) in northern regions. Furthermore, *Digitaria sanguinalis* and *Panicum* spp. cause problems in some regions.

The dicotyledonous weed *Chenopodium album* (Chenopodiaceae) was perceived as most important by the experts from all countries. Furthermore, *Amaranthus* spp. (Amaranthaceae), different Polygonaceae and *Solanum nigrum* (Solanaceae) are of significance in most regions.

In the northern regions, *Stellaria media* (Caryophyllaceae), *Calystegia sepium* (Convolvulaceae), *Geranium* spp. (Geraniaceae), *Veronica* spp. (Plantaginaceae), *Galium aparine* (Rubiaceae), and *Viola* spp. (Violaceae) were reported to cause problems. In the southern regions, *Convolvulus arvensis* (Convolvulaceae), *Abutilon theophrasti* (Malvaceae), and *Datura* spp. (especially *D. stramonium*) (Solanaceae) are significant weeds. Different species of Asteraceae occur in maize fields all over Europe, with *Cirsium* spp. being mentioned most often.

While only some weeds decreased in the recent years in some regions without consistent pattern, several taxa, e.g. *Panicum* spp., *S. halepense*, *C. album*, *C. sepium*, *Geranium* spp., and Polygonaceae showed increasing importance (Fig. 2). The facts that late germinating and perennial weed species are generally difficult to control and that the application of hormone-based herbicides has been reduced, may have contributed to this increase.

4.2. Herbicide applications

Weeds were controlled with herbicides in all European regions on more than 90% of the maize production area (Table 1). While applications in the pre-sowing stage were rare, herbicides were commonly applied before the seedlings emerged. The mean number of pre-emergence applications per season ranged from 0.1 in Southwest Poland and Denmark to 1.1 in Southwest France. Most herbicides, however, were applied post-emergence with the number of applications ranging from 0.4 in Southwest France to 2.3 in Denmark.

A broad range of active ingredients is used in Europe. This included ureas, triazine, pyridine, benzoylcyclohexanedione, amide, oxazole, aromatic acid, and nitrile herbicides.

Table 1. Area (%) of maize crop treated with pesticides in 11 European regions and number of applications.

Region	Herbicides		Insecticides				Fungicides
	Spray[a]		Soil application	Seed treatment	On-plant spray[b]		Seed treatment
Hungary Békés	100	(0.3 / 1)	50	20	40	(1)	100
Tolna	95	(0.3 / 1.1)	60	40	20	(1)	100
Italy Po Valley	96	(0.9 / 0.5)	5	80	11	(1)	100
Spain Ebro Valley	100	(1.0 /1.0)	10	100	50	(1-2)	100
France Southwest	98	(1.1 / 0.4)	42	0	6	(1)	100
Grand-Ouest	99	(0.7 / 1.0)	32	0	5	(1)	100
Normandie	100	(0.8 / 0.7)	33	0	2	(1)	100
Netherlands	99	(0.2 / 1.1)	0	50	0	-	95
Denmark	97	(0.1 / 2.3)	0	0	5	(1)	95
Germany Southwest	90	(0.2 / 0.9)	0	60	35	(1)	100
Poland Southwest	100	(0.1 / 1.3)	0	20	20	(1)	100

[a] number of applications pre-/ post-emergence in parenthesis

[b] number of applications in parenthesis

4.3. Options to reduce herbicide input

Integrated weed management, a component of IPM, allows to reduce herbicide input and to supplement control failures of herbicides by using non-chemical weed control including preventive, cultural and mechanical methods. At the same time, crop yield should not be compromised and a build-up of future weed populations should be avoided (Hiltbrunner et al., 2008). In the ENDURE activity "Integrated weed management" (Deliverable DR1.6) most of the major tactics of weed control presented in the following were developed and discussed.

Mechanical weed control in maize has been practiced in several European countries including Italy, France, Spain, and Hungary. For example in the Netherlands, 90% of the conventional farm area was managed with mechanical weed control between 2000 and 2005 because of political subsidies. Pre-emergence weed control often includes a stale seedbed, i.e. soil is prepared some time before sowing and sowing can even be delayed to allow as many weeds as possible to emerge prior to crop emergence. The field is then cultivated mechanically (by harrowing) before sowing and/or before crop emergence. Mechanical post-emergence weed control includes cultivation between the rows (mainly hoeing and harrowing) and within the rows (using finger-, torsion-, brush-, or pneumatic weeders). Further options include flame weeding before or after emergence and ridging later in the season (Van der Weide et al., 2008; Cloutier et al., 2007; van der Schans et al., 2006; Melander et al., 2005; Dierauer & Stöppler-Zimmer, 1994). In the future, precision weed control using innovative technologies (advanced sensing and robotics) might improve the efficacy of mechanical within row weed control and reduce the level of damage to the crop (Van der Weide et al., 2008).

Herbicide applications may also be reduced by fertilizer applications in surface or subsurface bands instead of broadcast applications to increase competition of maize against weeds (Riedell et al., 2000; Qin et al., 2005). Similarly, a narrower row space or higher plant density might improve competition if water and nutrient availability are not limiting factors (Teasdale, 1995; Murphy et al., 1996), but effects on weed biomass were not always apparent (Dalley et al., 2004; Johnson & Hoverstad, 2002). Reduced weed pressure may also be achieved with cover cropping (Moonen & Bàrberi, 2004; Melander et al., 2005), cleaning of machinery to avoid weed transfer between fields (Dierauer & Stöppler-Zimmer, 1994), and in irrigated fields when irrigation is delayed. Crop rotations with more crops in addition to maize may reduce weed proliferation, especially of weeds adapted to maize cropping, and allow the use of a wider range of herbicides, which lowers the risk of resistance development (Manley et al., 2002; Melander et al., 2005).

While purely mechanical and cultural methods are combined to replace labour intensive hand-weeding in organic farming, they can be applied in combination with herbicides (particularly band spraying) to reduce the amount of active ingredient in integrated farming systems (Baumann, 1992; Irla, 1994; Pleasant et al., 1994). For broadcast herbicide applications with reduced doses, the risk of resistance development might be limited by altering low with full doses in subsequent years. Dosages reduced to typically 50-80% of the rate recommended by the manufacturer have been already applied in maize on more than 50% of the area in the Netherlands and more than 80% of the area in Denmark, Germany, and France. In tillage systems without soil inversion (no ploughing), which provide improved soil quality and reduced erosion, often more herbicides are applied to avoid a build-up of weed seed banks. Ridge tillage systems combined with mechanical weed control, however, can be efficient even without herbicide inputs (Cloutier et al., 2007).

In many regions, **currently used sprayers** are often not sufficiently calibrated and applied herbicide doses are higher than needed. In the future, computer-based precision spraying has the potential to eliminate individual weed-plants or weedy patches with optimal doses that are calculated on-field (Kropff et al., 2008). Herbicides should be applied at the time when their impact on the weeds is highest. If pre-emergence weed control is optimized, the need for post-emergence measures may be reduced. Survey systems can provide decision support to the farmers for the selection of the most efficient weed control option by forecasting when weed populations exceed economic treatment thresholds. Several decision-support systems and expert models predicting weed emergence have been developed (Castro-Tendero & Garcia-Torres, 1995; Berti & Zanin, 1997; USDA, 2009; Masin et al., 2005, 2009). However, they are not yet used at farm or advisor level in Europe.

The cultivation of **genetically modified, herbicide tolerant crops** has the potential to reduce herbicide inputs. While some maize hybrids carrying this trait are in the process of authorization in the European Union (EFSA, 2009), herbicide tolerant maize hybrids were grown on more than 30 million ha worldwide in 2008 with increasing adoption rates (James, 2008).This technology allows adopting a different spray regime, where a broad spectrum herbicide (e.g. glyphosate) can be applied in postemergence when weed competition with maize is strongest. Growing herbicide tolerant crops provides the farmer with more flexibility than with conventional weed management, because weeds can be eliminated whenever needed (Kropff et al., 2008). Even though active ingredients and environmental impact were generally calculated to decrease with the use of herbicide tolerant crops, applied herbicide doses strongly depend on the local agronomic practice (Brookes & Barfoot, 2008). Thus regional guidelines and decision support systems for farmers need to be available to achieve optimal environmental benefits (Kropff et al., 2008).

5. Arthropod pests

Situation of arthropod pests in Europe

The most important arthropod pest of maize in Europe is the European corn borer, *Ostrinia nubilalis* (Lepidoptera: Pyralidae) (Fig. 3). In the infested areas, *O. nubilalis* is present in a large proportion of fields ranging from 20% in Hungary to 60% in Spain and estimated yield losses between 5 and 30% are typical without control measures. In France and Spain, the Mediterranean corn borer *Sesamia nonagrioides* (Lepidoptera: Noctuidae) cause additional economic damage (Fig. 3).

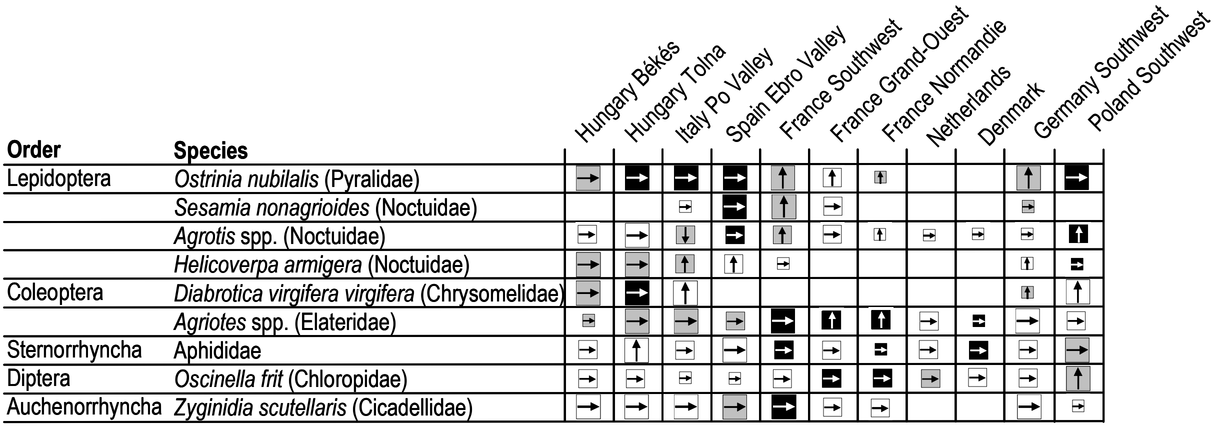


Fig. 3. Most important arthropod pests in European maize production. Significance is represented by symbol colour: black = high, grey = medium, white = low. Occurrence is represented by symbol size: large = widespread and regularly, medium = widespread and occasionally, small = regionally and rare. The 5-year population development is represented by arrows: up = increasing, horizontal = stable, down = decreasing

Between 2 and 4 million ha maize in Europe suffer from economic damage due to these corn boring pests (Brookes, 2009). Other Lepidoptera from the family Noctuidae include cutworms (*Agrotis* spp.) and the cotton bollworm (*Helicoverpa armigera*), which cause problems more in the central and southern countries (Fig. 3). Among Coleoptera, wireworms (*Agriotes* spp.) are reported to cause damage in all European focus regions. The western corn rootworm (*Diabrotica virgifera virgifera*) has been introduced into Europe in the 1980's and is currently invading the continent (Kiss et al., 2005, Meinke et al., 2009). In Hungary and other central and eastern European countries, populations have built up to a level causing economic damage. Among the studied regions, the pest has also reached Southwest Poland, Southwest Germany, and the Po Valley (Italy), but economic damage is not yet reported from those regions. Sap sucking pests, like aphids (Aphididae) and leafhoppers (Cicadellidae), as well as the frit fly (*Oscinella frit*) cause limited economic damage, although they are widespread and regularly occurring all over Europe (Fig. 3). Other pests of regional importance include armyworms (*Pseudaletia unipuncta*, Lepidoptera: Noctuidae) in Spain, different Diptera species (*Delia platura*, *Geomyza* spp., *Tipula* spp.) in Poland and France, different Coleoptera species (*Oulema melanopus*, *Glischrochilus quadrisignatus*, *Tanymecus dilaticollis*) in Poland and Hungary, spider mites (*Tetranychus* spp.) in Spain, Hungary, and Poland, and thrips (Thysanoptera) in Poland.

Within the last 5 years, populations of Lepidoptera pests including *O. nubilalis*, *S. nonagrioides*, *Helicoverpa armigera*, and *Agrotis* spp. were observed to expand and problems have increased (Fig. 3). More drastically, *D. v. virgifera* continues to spread in Europe with an average rate of 40 km per year (Kiss et al., 2005; Meinke et al., 2009). Efforts to eradicate the pest in regions where populations have not been established, e.g. in Southwest Germany and France, can help to delay the spread of the pest. In addition, population management in infested areas is important to reduce the speed of spread. Other pest species remained fairly constant, even though increases may occur in some regions with favourable conditions (e.g., soil, rainfall, cropping sequence). One such example is wireworms (*Agriotes* spp.), which increased in France (Fig. 3).

5.2. Insecticide applications

Insecticides, such as seed treatment, soil insecticides, and foliar applications were used in all European regions (Table 1). While seeds were not treated in France and Denmark, the total maize area where seeds were dressed with insecticides ranged from 20% in Békés county (Hungary) and Southwest Poland to 100% in the Ebro valley (Spain) with the other regions in between. Soil insecticides (e.g., thiamethoxam, tefluthrin, cypermethrin, clothianidine) were frequently applied in France and Hungary, where up to 60% of the maize area was treated (Table 1). The main target of seed treatments and soil insecticides in most regions are wireworms (*Agriotes* spp.). In Hungary, large scale treatments against western corn rootworm (*D. v. virgifera*) larvae were necessary. In Southwest Germany, seeds were also treated against corn rootworms in 2008 (U. Heimbach, personal communication), but adverse effects on honey bees has lead to a temporary ban of seed treatments in several regions.

Half of the maize area was treated with foliar insecticides in the Ebro Valley (Spain), followed by Békés and Tolna regions (Hungary), Southwest Poland, and the Po Valley (Italy). Less than 10% of the area was treated in France and Denmark and no insecticide sprays were applied in the Netherlands (Table 1). If treated, generally one application was done except the Ebro Valley, where two applications were also common. The main target of spray insecticides were corn borers (particularly in the Ebro Valley), but applications were also done against the western corn rootworm (mainly in Hungary) and other pests listed in Table 1. The most commonly used active ingredients in spray insecticides were pyrethroids and organophosphates, but oxadiazine, nicotinoid, carbamate, and diflubenzuron were also used.

5.3. Options to reduce insecticides

One alternative to insecticides for the control of *O. nubilalis* and *H. armigera* is **biological control** with *Trichogramma* spp. In Europe, the small wasps are released mainly against *O. nubilalis* on about 150,000 ha per year with the largest area in France. Cardboards with parasitized eggs are attached to the maize plants at the beginning of the egg-laying period. Efficacy (more than 75% destroyed pest eggs) and price (35-40 Euros for the first generation) are comparable to insecticides. One person can apply egg cards to 3-5 hectares per hour for first generation corn borer control. Forecast systems to determine the optimal time for application and efficient logistics are needed for successful application (F. Kabiri, unpublished data). Biological control may also become available for the control of corn rootworms (*D. v. virgifera*). Entomopathogenic nematodes achieved similar plant protection than conventional soil insecticides when applied to the soil early in the season. The application of entomopathogenic fungi also reduced corn rootworm damage, but with lower efficacy compared to nematodes and insecticides (Pilz et al., 2009).

Naturally occurring predators and parasitoids, which contribute considerably to biological control in the field, are often harmed by broad spectrum insecticide applications. A reduction in insecticide use would thus contribute to increased biological control. Natural enemies can furthermore be promotes with specific measures, including the establishment of a diverse mosaic crop pattern (Benton et al., 2003) and the management of field margins, e.g. flower strips and hedges to provide food, overwintering sites (Kiss et al., 1993; 1997; Denys & Tscharntke, 2002; Marshall & Moonen, 2002).

Genetically modified maize producing insecticidal Cry proteins derived from *Bacillus thuringiensis* (Bt maize) has been available for more than 10 years. In the EU, varieties expressing the Cry1Ab protein for the control of corn borers were cultivated in 7 countries on a total area of 107,000 ha in 2008. Most Bt maize was produced in Spain with an area of 79,000 hectares (James, 2008). In the Ebro valley, the area has been continuously increasing from 15% in 2002 to 65% in 2007. For the control of the western corn rootworm (*D. v. virgifera*)*, Bt* maize expressing Cry3 proteins became available in 2003. While those maize hybrids are already commercialized in the USA (Hellmich et al., 2008), they are in the authorization process in the EU. Due to the high efficacy of Bt proteins expressed in Bt maize hybrids, insecticides against the target pests are no longer needed. Furthermore, their high specificity ensures that the complex of natural enemies remains unharmed, and populations of non-target herbivores often remain below economic injury levels (Romeis et al., 2006, 2008). Brookes (2009) estimated for the use of Bt maize that at present only 14-25% of the potential environmental benefit from reduced insecticide use is being realized in the EU. The increase of adoption rates, however, is limited due to national bans of Bt maize, especially in countries with the highest potential benefit for the environment and farmers' economy, like Italy, France, Germany and Austria (Brookes, 2009).

Farmers have several **cultural options** to reduce arthropod pest pressure. Crop rotation is highly effective against the western corn rootworm, because adult beetles lay eggs mainly in maize fields, and the larvae starve if no maize roots are present when they hatch in the following year. Mowing stalks and/or ploughing are methods used by farmers in most European regions to reduce numbers of overwintering pupae of corn borers. Ploughing furthermore reduces populations of wireworms and cutworms. Against western corn rootworms, additional cultural methods include irrigation and fertilization to strengthen root regeneration after damage, and ridging to stabilize plants and prevent lodging. Furthermore, early planting may be favourable to allow the plants to develop a robust root system before larvae start feeding, and very late planting may also be an option, because most larvae have already hatched and starved. The planting of trap crops (e.g. susceptible hybrids or fodder grass) around maize fields may prevent *O. nubilalis* to enter the maize field for egg laying. A concentration of egg masses on the trap crop may limit the damage within the field and may attract natural enemies (Derridj et al., 1988; Stamps et al., 2007).

Synthetically produced sex pheromones can be used for mating disruption of stem borers. After releasing the pheromone in mating aggregation sites or in the field, male moths are no longer able to locate females, no mating occurs, and no fertile eggs are oviposited (Fadamiro et al., 1999; Albajes et al., 2002). In Europe, mating disruption has proved to be effective against *S. nonagrioides*, where populations could be reduced by more than 60% (Albajes et al., 2002).

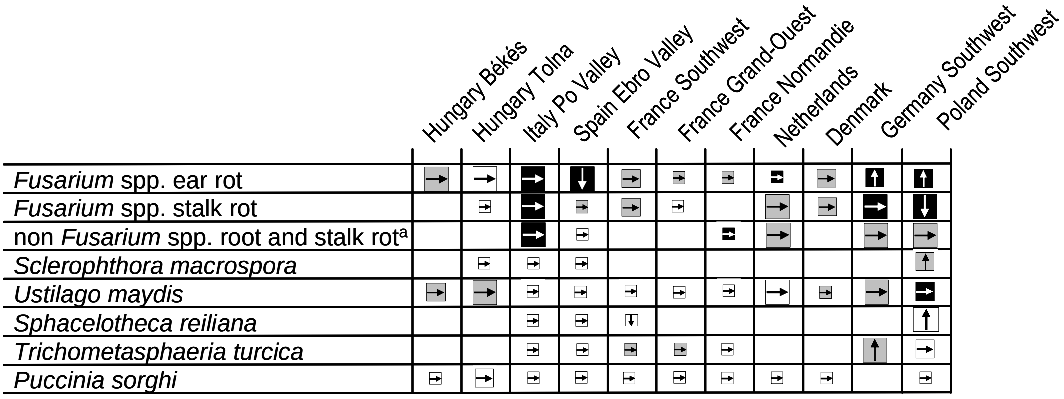
The use of semiochemical based insecticide baits is another option for western corn rootworm management in Europe. Cucurbitacin, a plant compound from watermelon which is highly attractive for rootworms, can be applied together with insecticide as a foliar treatment. Small doses of insecticide are sufficient to kill the adult beetles, which are attracted to the mixture (Buhler et al., 1998; Edwards et al., 1999).

Similar to herbicides, insecticide input may be decreased by **optimizing the currently used techniques**. Calibration of spray equipment may avoid the application of unnecessarily high doses. Furthermore, scouting and threshold-based decision systems should ensure that insecticides are only applied when economic threshold levels are exceeded. Scouting systems based on pheromone traps work well for determining the main flight and egg laying period of *H. armigera* (Dömötör et al., 2007) and *O. nubilalis*, which is vital for the success of biological and chemical control of this pest. Forecast systems for other pests, however, are currently not used in Europe. Particularly for the western corn rootworm, populations can be estimated by monitoring adults (Edwards et al., 1998; Komaromi et al., 2006), but predictions for potential yield losses in the following year are very difficult, because egg laying, and mortality of eggs and larvae are variable and patchy (Toepfer and Kuhlmann, 2005). Furthermore, the capability of plants to regenerate roots after feeding depends on water availability.

6. Fungal diseases

6.1. Situation of fungal diseases in Europe

Some *Fusarium* spp. causing ear, stalk and root rot were rated as the most economically significant diseases in most European regions (Fig. 4). The most dominant *Fusarium* species causing both stalk and ear rot was *F. graminearum*, followed by *F. verticillioides*, *F. proliferatum*, and *F. culmorum*, depending on different climatic conditions. One major problem with *Fusarium* spp. is the production of mycotoxins, like fumonisin, deoxynivalenol (DON) and T-2 (trichothecenes), and zearelenon (ZON), which lead to the contamination of human food and animal feed. Each of those toxins shows acute toxicity at low concentrations, ranging widely from temporal feeding disturbance to serious damage of several organs and even death (Bennett & Klich, 2003). Strict threshold levels for mycotoxins have been implemented in the EU (EC, 2007), but contaminations cannot always be kept below those threshold levels in grain maize production.



[a] *Phythium* spp., *Rhizoctonia* spp., *Acremonium* spp.

Fig. 4. Most important fungal diseases in Europe. Significance is represented by symbol colour: black = high, grey = medium, white = low. Occurrence is represented by symbol size: large = widespread and regularly, medium = widespread and occasionally, small = regionally and rare. The 5-year population development is represented by arrows: up = increasing, horizontal = stable, down = decreasing

Other fungal diseases of high importance in Europe are root and stalk rot caused by *Pythium* spp., *Rhizoctonia* spp. and *Acremonium* spp. Furthermore, *Sclerophthora macrospora*, *Sphacelotheca reiliana*, *Trichometashaeria turcia* (syn. *Helminthosporum turcicum*), *Ustilago maydis* and *Puccinia sorghi* may cause problems in some regions (Fig. 4).

While *Fusarium* stalk rot problems were reported to be stable in all regions, ear rot showed tendencies to increase in Southwest Germany and Southwest Poland. In Spain, ear rot decreased in the recent years (Fig. 4). This was most likely linked to the growing of *Bt* maize, which suffers less feeding by corn borers and provides less opportunities for *Fusarium* spp. to enter and infect the plants (Serra et al., 2008). Other fungal diseases remained fairly stable in the last five years.

6.2. Fungicide applications

More than 95% of the maize seeds planted in the European regions were treated with fungicides (Table 1). The most common active ingredients of seed treatments were amide, dithiocarbamate, and pyrrole fungicides. Foliar fungicide sprays were not used except on a small area in Southwest France against *Helminthosporium* spp., *Fusarium* spp., and *Puccinia* spp.

6.3. Options to reduce fungicides

Because options to protect maize against fungal diseases are limited, great effort has been made in breeding of varieties that provide certain resistance (Snijders, 1994). Official rankings, which show the susceptibility of different varieties to *Fusarium* spp. ear and stalk rot, are available in many countries.

Fungal diseases often enter the maize plant through feeding wounds caused by arthropod pests, especially 2nd generation corn borer larvae feeding on maize ears (Sobek & Munkvold, 1999). In addition, many insects are known to transfer inoculums of fungal diseases between plants (Dowd, 2003). Consequently, strategies to prevent feeding damage, including Bt maize and chemical insecticides, can help to reduce fungal diseases and associated mycotoxin problems (Dowd, 2003; Blandino et al., 2008c; Serra et al., 2008; Papst et al., 2005).

Fusarium spp. development is favoured by high levels of moisture during the maturation period of the crop (Lacey & Magan, 1991). Options to reduce exposure to humid conditions, which occur frequently in autumn, include early planting (and consequently harvesting) of maize (Blandino et al. 2008c) or the use of early maturing varieties (Blandino et al., 2008a). In addition, early planting may result in reduced feeding damage by corn borers, because the time of infestation may occur in a physiological stage that is less attractive for the insects (Derridj et al., 1989). Mycotoxin contamination of kernels may also be reduced when maize crop is cultivated at low plant densities, because of a less humid microclimate that limits fungal growth inside the crop (Blandino et al., 2008a). Furthermore, the type and amount of applied N fertilizer can influence the accumulation of different mycotoxins. Balanced fertilizing (200 kg/ ha) resulted in lowest mycotoxin contamination in an Italian study (Blandino et al., 2008b).

Cultural methods to reduce the amount of initial inoculums of *Fusarium* spp. include crop rotation with non-host crops (no cereals) and ploughing of infested residues.

A biological control system using an endophytic bacterium, *Bacillus subtilis*, showed promise for reducing mycotoxin accumulation during the endophytic growth phase of *F. moniliforme*. Because this bacterium occupies the identical ecological niche within the plant, the inhibitory mechanism, operates on the competitive exclusion principle (Bacon et al., 2001).

In general, there is a need for survey systems to predict disease damage and mycotoxin production. If the actual risk would be known early in the season, farmers could react, e.g. by adjusting harvest time and by deciding on the final use of the harvest. Model based approaches to predict disease incidence and mycotoxin contamination are available (Samapundo et al., 2005, 2007; Battilani et al., 2003, 2008). Furthermore, a software tool predicting mycotoxin levels more than a month before harvest, using temperature, soil type, numbers of insects and other factors that influence the moulds' growth and spread, exists in the USA (Mycotoxin Predictor 1.1) (Dowd, 2005). However, no such software tool is used in European maize production.

7. Major constraints of alternative pest control methods

Currently used chemical pesticides are usually relatively cheap and efficient, supply chains exist and growers are equipped to apply them. Several restrictions need to be overcome for alternative pest control methods to be adopted. While those restrictions may be overcome for some strategies within a few years, other options will need more time and effort until they can be implemented in agricultural practice.

7.1. Availability

Before new pest control strategies can become agricultural practice, they need to be available to the farmers. Several restrictions on availability may occur: First, the technology or machinery is not yet developed for commercial use. One example is weed control, where intelligent weeders and equipment for precision spraying are still under research and development. However, mechanical weed control is an option that is practiced already in several countries. Second, non-chemical methods, new pesticide application techniques and reduced doses are all methods which need to be adapted to regional conditions. In some cases, local adaptation is difficult or may even be impossible, even though the method is practised successfully in other regions. For example, appropriate timing of post-emergence weed control is more difficult under a Mediterranean environment with highly dynamic weed emergence than under a northern European climate. Furthermore, mechanical weed control may lead to additional loss of soil moisture, which is undesirable in areas with limited water availability. Another example is biological corn borer control with *Trichogramma*, which is successfully commercialized in some regions, but seemed to lack efficacy in others (Schröder et al., 2006). Third, a pest control method may work against one pest, but might not be transferable to another pest. One example is semiochemical-based pest control, which is available as attract- and kill products against the western corn rootworm, but efficacy with several insecticides registered for foliar application in maize should be tested. Furthermore, no such product exists against corn borers in Europe. Multiple strains of the European corn borer co-occur in Europe and their control requires multi-strain attractants, which are not available yet. However, a pheromone-based strategy that combines European and Mediterranean corn borer control might become an economically viable alternative to common pest control methods in the future (Eizaguirre et al., 2007). Finally, working products may be available, but authorization is denied by regulatory agencies. This is particularly the case for genetically modified, herbicide tolerant or insect resistant, maize varieties in Europe.

7.2. Organization

Alternatives to chemical pesticides often require a reorganization of cultivation steps. For example, *Trichogramma* egg cards for corn borer control need to be applied within a few days of the season and depending on farm size, additional workers may be needed. Furthermore, exact timing of many pest control methods (*Trichogramma*, mechanical weed control, pheromone-based methods, etc.) requires certain flexibility of the farmers. Some organizational restrictions for new strategies may not be overcome by individual farmers, but may open a perspective for specialized contractors that are adapted to the specific requirements and can provide specific services. For example in the Po Valley (Italy), many farming services (e.g. sowing or pesticide applications) are provided by contractors, because many part-time farmers do not have enough time or appropriate equipment. Alternatively, sharing of new equipment is another option for farmer groups to increase efficacy and to lower costs for each individual, even though a certain reorganization of the farm processes might be necessary.

7.3. Farmers' knowledge and training

Alternative pest management strategies need knowledge and skills of the operators and can only work on a commercial scale if research and development is closely linked to consultants and farmers. Farmer-researcher partnerships (Karlen et al., 1995) and farmer participation in commercial field trials is most likely to produce trust in new techniques with the potential that success motivates other growers to follow. In addition, farmer schools including field training days and education for consultants are important to establish new methods. For example, good experiences were reported from participatory farmers training under a regional FAO project from Central Europe (Komaromi and Kiss, 2005; Komaromi et al, 2005).

7.4. Economics

Environmentally friendly methods for efficient pest control also need to be economically attractive, because costs are naturally a very critical factor in farmers' and suppliers' choice of crops and methods. Political initiatives including subsidies or authorization rules might be required initially to overcome economic restrictions and to change their choice. However, new strategies can only be sustainable if they provide longer term benefits and are economically competitive with current strategies.

The application of new strategies can lead to several economic consequences: First, the purchase of new machinery or the backfitting of machinery to new cultivation methods often require major financial investments. This restriction, however, may provide an opportunity for specialized contractors or groups of farmers working together. Second, the new production system including production costs, yield and market price of maize and alternative crops need to result in an income for the farmer comparable to the previous system, even though heterogeneous rotations could mean that less profitable crops have to be grown in some years (Karlen et al., 1995). Crop rotations with new crops require infrastructure and markets to ensure that the new products can be sold. Furthermore, the application of a new method should not result in a reduced yield and consequently a lower income. Potential reasons are low efficacy of pest control, negative impact of the method itself on crop growth, and increased risk of failure of the new method. Third, more time consuming methods result in increased costs for labour, especially if precise timing is needed, e.g. for mechanical weed control (Karlen et al., 1995; Brumfield et al., 2000). Labour availability is likely to represent restrictions for large farms specialized on maize production than on small, diversified farms. In addition, costs for the time consuming scouting of pest populations come with the adoption of IPM systems (Brumfield et al., 2000).

7.5. Interactions of different strategies

For new crop management strategies applied to solve one particular problem, potential consequences for other pest complexes need to be considered. Ideally, the new method contributes to solve several pest problems simultaneously, like Bt maize, which is controlling corn borers and consequently leads to decreased *Fusarium* spp. problems. While interactions are generally limited for rather specific methods (e.g. mechanical weed control, biological control, Bt maize), cultural methods often have complex consequences on the cropping system. One example is the early planting of maize, which may decrease *Fusarium* problems, but at the same time may increase weed pressure and difficulties in weed control (Otto et al., 2009). Another example is crop rotation, which can solve western corn rootworm and weed problems, but might increase *Fusarium* diseases, if the rotation consists mainly of cereals. Furthermore, no tillage systems are known to improve soil functions and to decrease erosion, but problems with weeds, corn borers, wireworms, and fungal diseases are also likely to increase.

One possibility to address the broad range of consequences of different management strategies is the use of multicriteria assessments. Many parameters can be weighed and linked with each other to find scenarios with most positive and least negative interactions. Multicriteria assessments are developed in the ENDURE activities RA3.1 and RA2.4. Monitoring programs may then help to decide which strategy is most appropriate under the current conditions in a specific region.

8. Conclusions

Our survey revealed that maize production systems show differences in several European regions. While mainly silage maize is produced in the North, grain production dominated in central and southern Europe. Furthermore, crop rotation ranged from maize monocultures to well planned rotation systems. Despite those differences in maize cropping, a common set of weeds, arthropod pests and fungal diseases are responsible for the main problems in most European countries, even though some differences exist between countries, particularly between the north and in the south. We furthermore recognized that several weeds and arthropod pests cause increasing problems, while decreases were reported only rarely. Diseases remained fairly stable. Given that pesticides are currently the most commonly used method to control weeds, arthropod pests and diseases in maize, this illustrates that the goal of reducing pesticide applications is a big challenge.

Options to reduce the input of harmful substances into the maize agro-ecosystem include the choice of varieties and cultural methods, the optimization of application techniques of chemicals, and the development of more specific treatments. While some strategies need further development or more field research before they can become agricultural practice, other methods have already proven to work under commercial conditions. This includes mechanical weed control, biological corn borer control, or the use of genetically engineered maize varieties. However, restrictions in availability, organization, and education and knowledge, need to be overcome before environmentally friendly pest control strategies can replace chemical pesticides in an economically competitive way.

The presence of several problems that need to be tackled simultaneously indicates the need for IPM approaches, which combine the most efficient environmentally friendly methods to maintain the ecological balance of the crop production system. The fact that cultural methods (e.g. crop rotation, changes in sowing date or tillage) may interfere with each other demonstrates that pest control needs to be seen in the context of the whole cropping system and on a regional scale (Melander et al., 2005). If the cropping system comprises several crops and is modified to counteract negative consequences, pest control-failures in one crop with one specific method become less important. The compilation and analyses of pest problems, pesticide input and alternative options and restrictions provided in this study should represent a good basis for further discussion and development of advanced crop protection strategies with reduced input of chemical pesticides in European maize production.

9. Knowledge compilation for advanced pest control in maize production

During the Maize Case Study, the involved partners were collecting information about advanced pest control methods that are less relying on pesticide use. The partners presented their information at the Maize Case Study meeting on 2-3 April 2009 at Agroscope Zurich. These presentations are online available on the ENDURE website, collaborative workspace, ENDURE Activities, RA1.2 Maize Case Study, Knowledge compilation for advanced pest control. The names, contents and authors of those documents are listed in the following.

1_Options and restrictions to reduce pesticide use_Hungary
Title: Option & Restrictions to reduce pesticide use in Hungary.
Insects, weeds, pathogens
Authors: Zoltan Pálinkás, Jozsef Kiss, Ágnes Szénási

2_Options and restrictions to reduce pesticide use_Italy
Title: Options and restrictions to reduce pesticide use for maize case study.
38 ideas (Weeds: 10; Insects: 15; Disease: 1; Mycotoxin: 12)
Field margin complex.
Authors: Vasileios Vasileiadis, Daniele Antichi, Stefan Otto

3_Options and restrictions to reduce pesticide use_Spain
Title: Option & Restrictions to reduce pesticide use in Spain.
Options and possibilities to overcome restrictions; estimated applicability. Mainly for arthropod pests but also for diseases and weeds
Author: Xavier Pons

4_Options and restrictions to reduce pesticide use_NL DK_2009
Title: Options and restrictions for Netherlands and Denmark
Physical weed control in conservation tillage systems. Pre emergence harrowing and reduced dos. Stale seedbed and reduced dose. Hoeing and band spraying
Only mechanical control (harrowing and ridging). GMO-HT. Ridge tillage.
Authors: Rommie van der Weide, Bo Melander, Ghita Nielsen

5_Biocontrol_Overview_2009
Title: Biological opportunities for the protection of maize.
Overview of alternative control measures for weeds, arthropod pests and diseases according to stages: registered commercial use/ in development/ research
IPM approach.
Author: Bernard Blum

6_Biocontrol_Nematodes for Diabrotica control_2009
Title: Control of the invasive alien maize pest Diabrotica v. virgifera using nematodes.
First results of field experiments with entomopathogenic nematodes (EPN).
Authors: Stefan Toepfer, Ralf Udo Ehlers, Benedikt Kurtz, Regina Burger, Ulrich Kuhlmann

7_Biocontrol_Trichogramma for ECB control_2009
Title: *Trichogramma* against the European Corn Borer: The main outdoor utilization of beneficial.
Commercial use for more than 20 years.
Experiences in France.
Public and private cooperation.

Author: Firouz Kabiri

8_Bt-Maize_nontarget species_2009
Title: Selecting non-target species for regulatory risk assessment of GM maize.
Building a database, adapting PRONTI database format.
Authors: Simon Knecht, Franz Bigler, Jörg Romeis

9_IntegratedWeedManagement_IWM_2009
Title: Integrated Weed Management (IWM).
Overview; conclusions for IWM in maize. Stale seedbed and pre-emergence cultivation, inter-row cultivation, band-spraying.
Authors: Bo Melander, Nicolas Munier-Jolain, Paolo Barberi, Rommie van der Weide, Arnd Verschwele, and Maurizio Sattin

10_Fusarium and mycotoxins_2009
Title: Maize – fungal pathogens interaction – detection methods.
Yield components of maize
Yield components – development stages of maize- stresses
Leaf disease, ear diseases, detection methods
Author: Elzbieta Czembor

11_Forecast and warning systems_2009
Title: Possible future situation in Italy concerning “Forecast/ Warning systems”
Survey system for O. nubilalis and Diabrotica
Expert system for weed control
Authors: Vasileios Vasileiadis, Daniele Antichi, Stefan Otto

12_Life cycle assessment_2009
Title: Maize case study – Life cycle assessment
Methodology
Results from Denmark, France and Italy.
Conclusions
Author: Frank Hayer

13_Economic data_2009
Title: Maize Case Study Meeting - economic data
Hungary, Spain, Italy, France, Netherlands and Denmark
Authors: José Hernandez, Gabi Mack

10. Leaflets

The leaflets contain ready to use information for extension services, advisers and farmers on alternative methods to control key pests in maize. They will be disseminated by the ENDURE website. Leaflet 1 is in the process of publishing (with A. Lewer); leaflets 2 and 3 are drafts.

Leaflet 1: Non-chemical control of corn borers using *Trichogramma* or *Bt* maize

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From Science to Field
Maize Case Study – Guide Number 1

Non-chemical control of corn borers using *Trichogramma* or *Bt* maize

Michael Meissle, Franz Bigler, Agroscope ART, Switzerland
Firouz Kabiri, Biotop, France
Xavier Pons, Universitat de Lleida, Spain

Larva of European corn borer © Gabriela Brändle, Agroscope ART, Zurich, Switzerland

From Science to Field
Maize Case Study – Guide Number 1

Non-chemical control of corn borers using *Trichogramma* or *Bt* maize

Corn borer problems in Europe

Biology & distribution. The European corn borer (*Ostrinia nubilalis*, ECB) is a widespread and major pest of maize in Europe. The small nocturnal moths lay clusters of 10-40 eggs on the lower leaf surface. Larvae chew leaves and tunnels in the stems of the maize plants, which weakens the plants and causes them to break. Furthermore, the ears of maize can be damaged. While the pest has one generation in Northern Europe, two to three generations occur in the Southern countries. Developed larvae overwinter in maize stubbles. In Mediterranean countries, another stem boring species, the Mediterranean corn borer (*Sesamia nonagrioides*, MCB), may cause most serious damage. Its life cycle is similar to that of ECB, but females lay eggs between the sheath and the stem of maize plants. Because larvae enter the stem just after hatching, they are always protected from both natural enemies and chemical insecticides.

Damage. Due to the tunnelling of the larvae, stems often break and complicate harvesting. Reduced plant development and nutrient transport result in yield losses of about 7% in average and up to 30% when fields are heavily infested. In sweet maize production, ears with feeding damage are not marketable. Furthermore, wounds caused by corn borer feeding facilitate infestation by fungal diseases. Mycotoxins, which are produced by some growing fungi, can lead to quality reductions of the grains if the allowed threshold levels are exceeded.

Insecticides. In the European Union, about 0.7-0.9 million ha are treated with insecticides against corn borers. However, spray insecticides or on-plant microgranulates are only efficient when applied before larvae of ECB enter the maize stems. With maize plants being one meter or higher at this stage, special equipment is necessary. In addition, commonly used insecticides (e.g. Oxadiazine, Pyrethroid, Organophosphates) are known to have adverse effects on non-target arthropods including natural enemies and pollinators.

Cultural methods. Cutting stems close to the ground and ploughing plant remains under in autumn or early spring are methods used to reduce the number of emerging adults and thus the number of eggs laid in the new crop. However, no-till or reduced tillage methods would be more suitable in some areas in order to preserve the soil.

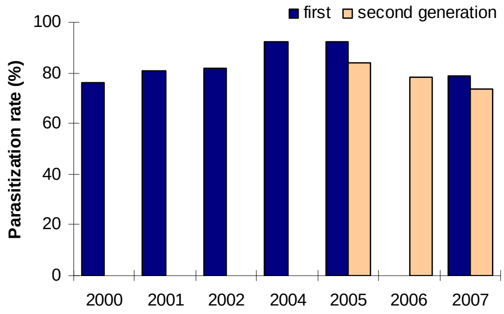
Trichogramma egg card applied to a maize plant
© Biotop, Valbonne, France

Trichogramma – a biological control alternative

Biology. *Trichogramma* species are microscopic wasps (<1mm) that search and parasitize eggs of ECB. New *Trichogramma* wasps develop from egg to adult in the host eggs. Until now, about a dozen of the worldwide 200 species are commercially used. Against ECB, the most effective species is *Trichogramma brassicae*. The wasps need to be released every year because they are not able to overwinter in large numbers under European conditions. However, *Trichogramma* is not able to parasitize the hidden eggs of the MCB.

Application. Egg cards containing *Trichogramma* wasps can be attached easily to the maize plants by hand at the beginning of the egglaying period of the ECB. The optimal date of release can be forecasted reliably based on temperature sum, caterpillar pupation surveys and trapping of first adults. The product can be customized to different crop types (grain, silage, seed or sweet maize). Against the first generation of the pest, 100- 225 thousand wasps are released usually ones from 25-50 release points per hectare. An area of 3-5 hectares can be covered per hour and person. *Trichogramma* can also be released against the second generation of ECB. High levels of infestation, warm temperatures and higher plants typically require 225- 600 thousand wasps from 50 release points per hectare and more time for application (2-3 hectares per hour and person).

Adoption. Since first commercialization of *Trichogramma* in 1980, the technique has been improved continuously. By now, wasps are released on about 150,000 ha, mainly in France, Germany and Switzerland every year.



Parasitization rate of first and second generation ECB after mass release of *Trichogramma* wasps

Source: Biotop, Valbonne, France

Efficacy. *Trichogramma* wasps have been developed to a product with high reliability. If the manufacturers' recommendations are followed, the efficacy is comparable to chemicals and more than 75% of the ECB eggs are commonly parasitized and destroyed. In areas where–ECB has 2-3 generations per year, a good control of the first generation is crucial to reduce attacks of the following generations and to get better global results.

Environmental risks. Some *Trichogramma* wasps may leave the maize fields and parasitize eggs of non-target insects. However, field studies have shown that parasitization rates in natural habitats around maize fields remained low after the mass release of *Trichogramma*. Furthermore, parasitization of natural enemies as well as competition with indigenous egg parasitoids was found to be insignificant under field conditions. Most of the released wasps die after the egglaying period of ECB. Cardboards of egg cards are biodegradable and there are no known risks for human health. The product can thus be considered environmentally friendly.

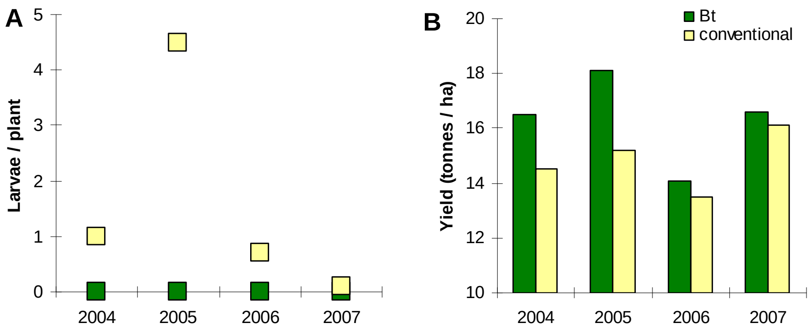
Costs. The costs of biological control using *Trichogramma* depend on countries, distribution systems and doses. In France for example, the end-user price against the first generation of European corn borers is about 35-40 Euros per hectare (excluding costs of labour) and thus comparable with chemical insecticides (ca. 20-40 Euros per hectare). For the control of the second generation, the end-user price can be calculated at 45-55 Euros per hectare.

Maize producing insecticidal *Bt* protein against corn borers
© Michael Meissle, Agroscope ART, Zurich, Switzerland

Bt maize – a new technology against corn borers

Characteristics. Genetically engineering has been used to develop maize plants that produce an insecticidal protein from the bacterium *Bacillus thuringiensis*. The insecticide is expressed over the whole growing season in the whole plant, which allows efficient control of stem boring moths like ECB and MCB.

Adoption. In the European Union, *Bt* maize for corn borer control is approved since 1998, even though some countries prohibit its cultivation. By now, many *Bt* maize varieties containing the transformation event MON810 are registered in the European catalogue of varieties. In Europe, 108 thousand hectares of *Bt* maize were grown in 2008, with Spain representing 75% of the total area.



Number of corn borer larvae (A) and yield average (B) in *Bt* maize compared with conventional maize in Catalonia, Spain

Source: Salvia et al (2008). DARP, Generalitat de Catalunya, Dossier Técnic 27: 3-14

Efficacy. *Bt* maize provides an almost 100% protection against all generations of corn borers and most larvae die shortly after feeding.

Environmental risks. A large number of laboratory and field trials have revealed no detrimental effects of *Bt* maize on beneficial arthropods, like natural enemies, soil organisms, or pollinators. *Bt* proteins are harmless to humans and animals. Currently available *Bt* maize varieties produce low toxin concentrations in pollen, which minimizes the risk for moths and butterflies outside the maize field. Maize has no wild relatives in Europe, thus outcrossing poses no environmental risk. To ensure the coexistence of conventional cultivars with *Bt* plants, minimum distances (defined by the countries) to neighbouring non-*Bt* maize fields have to be respected by the farmers. Furthermore, farmers are required to plant a certain percentage of conventional maize to reduce the likelihood of resistance development, in Spain for example, 20% for fields larger than 5 hectares. In some countries, fields cropped with *Bt* maize have to be documented in a public register.

Costs. When buying *Bt* maize seeds, farmers need to pay a “technology fee” in addition to the price of conventional maize. This fee is defined by the seed companies and may vary from region to region. For example in the Lleida region (Catalonia, Spain) with medium to high corn borer pressure, Bt maize is 40-45 Euros per hectare more expensive than conventional maize. In contrast to other control methods, however, farmers have no extra costs for labour, machinery or chemicals.

Summary

Corn borers are widespread and major pest of maize in Europe causing yield losses up to 30%. One alternative to chemical insecticides against the European corn borer is biological control with the egg parasitoid *Trichogramma brassicae.* The small wasps are released on about 150 thousand ha in Europe per year, mainly in France. Egg cards containing the wasps are attached to the maize plants at the beginning of the egglaying period. Efficacy (more than 75% destroyed pest eggs) and price (35-40 Euros for the first generation) are comparable to chemicals.
Genetically engineered maize that produces an insecticidal protein from the bacterium *Bacillus thuringiensis* is another option to control corn borers including the Mediterranean corn borer, which cannot be controlled using insecticides or *Trichogramma*. In Europe, 108 thousand hectares of *Bt* maize were grown in 2008, mainly in Spain. *Bt* maize provides almost 100% protection against all generations of corn borers. No detrimental effects of *Bt* maize on the environment and human and animal health have been reported. *Bt* maize seeds are usually more expensive than conventional seed, but farmers have no extra costs or labour for corn borer control.

In conclusion, biological control with *Trichogramma* and *Bt* maize are two efficient and competitive options for corn borer control to reduce the amount of chemicals released into the environment.

For further information please contact:

Firouz Kabiri, BIOTOP
Route de Biot – D4, 06560 Valbonne, France. Tel: (+33) 493123790
E-mail: *fkabiri@biotop.fr*

Xavier Pons, Universitat de Lleida
Rovira Roure 191, 25198 Lleida, Spain. Tel: (+34) 973702824
E-mail: *pons@pvcf.udl.cat*

Franz Bigler, Agroscope Reckenholz-Tänikon ART
Reckenholzstrasse 191, 8046 Zurich, Switzerland. Tel: (+41) 443777235
E-mail: franz.bigler@art.admin.ch

Leaflet 2: Prevention of *Fusarium* ear rot of maize and mycotoxin accumulation

From Science to Field
Maize Case Study – Guide Number 2

Prevention of *Fusarium* ear rot of maize and mycotoxin accumulation

Elzbieta Czembor, Plant Breeding and Acclimatization Institute (IHAR), Poland
Jozef Adamczyk, Smolice Breeding Comp. Poland
Stephanie Schürch, ACW Changins, Switzerland
Katalin Posta, Plant Protection Institute Szent Istvan University, Hungary

Elzbieta Czembor, IHAR, Poland

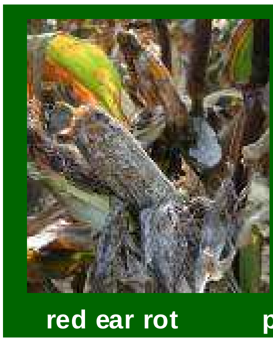
Prevention of Fusarium ear rot of maize and mycotoxins accumulation

Ear rot problems in Europe

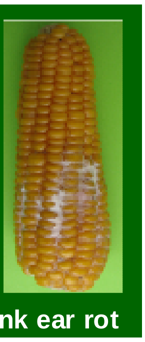
However more than 95% of the maize seeds planted in the European regions are treated with fungicides many maize fields develop disease problems every year that affect yield and quality of the grain crop. *Fusarium* spp. causing ear rots are the most economically significant diseases in most European regions which showed tendencies to increase in Europe except Spain where it decreased in the recent years.

Biology and distribution of *Fusarium* spp.

Many maize fields develop disease problems every year that affect yield and quality of the grain crop. The major maize fungal diseases can be grouped into four categories: leaf blights, stalk rots and ear rots. Ear and kernel rots decrease yield, quality, and feeding value of the grain. One of the most important diseases is red ear rot and pink ear rot. Red ear rot id caused by *Fusarium graminearum* and pink ear rot is caused by *F. verticillioides*, *F. proliferatum* and *F. subglutinans*.



red ear rot



pink ear rot

Elzbieta Czembor, IHAR, Poland

In red ear rot, infection starts at the tip of the ear just after the female flowering time and moves toward the base. Typically the husks are also infected and fuse with the ear. In pink ear rot, infection tends to be more uniform, with no real concentration at the tip.

Corn borer

Impact of corn borer on pink ear rot disease

Symptoms of pink ear rot are often highly correlated with ear damage by European corn borer larvae (*Ostrinia nubilalis* Hbn.). Larvae cause physical injuries to stalk and ears, and promote infections by *Fusarium* spp. In addition, European corn borer larvae can carry fungal inoculum from the plant surface into the kernels.

European corn borer larvae carry spores of *Fusarium* species from the plant surface to the surfaces of damaged kernels or to the interior of stalks, where infection occurs. Viable spores can be found externally, internally, and in the frass of European corn borer larvae. A second type of interaction is through formation of entry wounds for the fungi when larvae feed on stalks or kernels. Even when the larvae do not directly carry the fungi into the stalks, spores subsequently deposited on the wounded tissue are very likely to germinate and infect the plant, although the overall importance of insect tunneling in stalk rot development is a matter of some disagreement among plant pathologists.

Mycotoxins accumulation in food and feed and health effects

Infection by *Fusarium* spp. results not only in yield reduction but also in contamination with mycotoxins. The most important mycotoxins are: deoxynivalenol (DON), nivalenol (NIV) and zearalenone (ZEA) (produced by *F. graminearum*) and fumonisins (FB1 and FB2) and moniliformin (MON) (produced by *F. verticillioides*). Mycotoxins are resistant to high temperatures and chemicals. They can accumulate in grains, heavily contaminate grain-based food and feed, and they can cause many diseases.

Maximum levels of *Fusarium* mycotoxins in maize for human consumption
[Commission regulation (EC) No 1126/2007].

Product	Deoxynivalenol (DON) [µg/kg]	Zearalenone (ZEA) [µg/kg]	Fumonisins (FUM B1 + FUM B2) [µg/kg]
Unprocessed maize with the exception of unprocessed maize intended to be processed by wet milling	1 750	350	4 000
Maize intended for direct human consumption	780	100	1 000
maize-based snacks and maize-based breakfast cereals	500	100	800
Processed cereal-based foods and baby foods for infants and young children	200	20	200
Milling fractions of maize with particle size > 500 micron falling within CN code 1103 13 or 1103 20 40 and other maize milling products with particle size > 500 micron not used for direct human consumption	750	200	1 400
Milling fractions of maize with particle size ≤ 500 micron falling within CN code 1102 20 and other maize milling products with particle size ≤ 500 micron not used for direct human consumption	1 250	300	2 000
Refined maize oil		400	

For animal feeding the limits are between 2 000 and 8 000 µg kg^{-1} for DON and FUM and 250-500 µg kg^{-1} for ZEA depending on the feeding stuff and animal species. Deoxynivalenol or DON (Vomitoxin) decreases feed intake and reduces weight gain of pigs at concentrations of about 2 000 µg kg^{-1} of feed. T-2 and HT-2 toxin are more toxic than DON and cause reduction of feed intake, vomiting, irritation of the skin e. g. tract, neurotoxicity, taratogenicity, impaired immune function and hemorrhage. Adverse effects seen in farm animals are generally caused by toxin mixtures rather than by single toxins. Zearalenone causes reproductive problems such as infertility and abortion in livestock, especially swine. Fumonisin B1 has cancer-promoting activity in rats, causes equine leukoencephalomalacia, and is associated with porcine pulmonary edema.

Disease management factors

As no really good chemical control in the field is possible, prevention relies on cultural practices, on disease management factors.

Management Factors	Impact
Strategic	
Crop rotation	High
Crop residue management	High
Good nutrient supply	Medium
Tactical	
Variety choice	Medium
Seed quality	Low
Sowing time	Low
Crop structure	Low
Control measures	
Disease control	Low
Weed control	Low
Insect Control	High
Harvest and storage	High

Crop rotation. The main inoculum source for red and pink ear rots of maize are crop residues of preceding diseased crops. The best documented example is the high risk of ear rot when maize is grown in monoculture or after wheat. Maize stubble are often colonized by the same *Fusarium* spp. as the ones affecting wheat and these *Fusarium* spp. can survive and multiply on maize stubble for several years.

Crop residue management. Three removing methods are recommended: physical removal, using specially designed vacuum cleaners and biological crop residue treatments. Microbial decomposition of crop residues is a natural process which can be supported by adding stimulating nutrients or selected micro-organisms.

Using cultivator it is possible to mix mulched maize residues into the ground for the decomposition (especially in the soil zone under active conversion, to promote rotting). Mechanical cutting of plant residues before basic tillage is recommended to minimalist infection and to promote rotting.

Good nutrient supply for the plants
Maize plants can be predisposed to Fusarium infection by high levels of nitrogen and low levels of potassium.

Variety choice The most effective method to control red and pink ear rots is to use resistant hybrids. Two types of ear rot resistance are identified in maize. Silk channel resistance prevents the fungus from invading through the silk channel down to the kernels. Kernel resistance blocks the spread of the fungus from kernel to kernel. Resistance to *Fusarium* spp. is quantitatively inherited, but until now no fully resistant maize genotype is known. The relationships between resistance and mycotoxin contamination are reported. Hybrids that have been holding their ears vertically and have poor ear cover can be more susceptible to pink ear rot. Hybrids with tight husks appear to be more vulnerable to read ear rot.

Bt maize Maize cultivars carrying the Bt gene are highly resistant to European corn borer larval feeding. In addition, maize hybrids expressing the Bt gene were found to be less infected with *Fusarium* spp. and showed lower mycotoxin concentration in kernels.

Control measures

Chemical control In the case of systemic infections of maize plants with *Fusarium* spp., application of fungicide early in the season can limit ear infection. When pink or red ear rot diseases develop late in the season, the use of fungicide is not appropriate. If the *Fusarium* spp. has already attacked maize plants, harvesting as soon as possible.

Insect management Management of insect pests will reduce infection of *Fusarium* spp. For example arthropod pests often transmit viruses causing stress for plants, and feeding wounds facilitate infection by pathogens, e.g. *Fusarium* spp. European corn borer larvae carry spores of Fusarium species from the plant surface to the surfaces of damaged kernels or to the interior of stalks, where infection occurs.

Harvest and storage

The disease can continue its development during storage of ears under the conditions of high humidity and insufficient aeration. For this reason, harvested grain should be dried to 15%moisture content or below, to prevent mold growth in storage. Good storage conditions like proper temperature and moisture content, aeration, insect control and clean bins will lower significantly the risk of any grain infection.

Summary

Red and pink ear rot diseases caused by *Fusarium* spp. occur widely throughout maize growing regions of the world. Infection appears on the surface of ears at the end of the milky stage or in the beginning of waxy stage. If the mold is thick, the grains are destroyed. *Fusarium* spp. are the causal pathogens which produce mycotoxins. The most important are deoxynivalenol, nivalenol, zearalenone, fumonisins and moniliformin. They are suspected to cause immunosuppression, embryo abortions and deformations, swine enderogenic syndrome, porcine pulmonary edema, liver cancer in rats and human esophageal cancer. In conclusion, crop rotation, removing of crop residues, variety choice (including Bt maize), insect management and good storage have the highest impact on the level of the diseases and on the mycotoxins contamination.

For further information please contact:
Elzbieta Czembor, IHAR Radzikow,
05-870 Blonie, Poland
e.czembor@ihar.edu.pl

About ENDURE

ENDURE is the European Network for the Durable Exploitation of Crop Protection Strategies. ENDURE is a Network of Excellence (NoE) with two key objectives: restructuring European research and development on the use of plant protection products, and establishing ENDURE as a world leader in the development and implementation of sustainable pest control strategies through:
> Building a lasting crop protection research community
> Providing end-users with a broader range of short-term solutions
> Developing a holistic approach to sustainable pest management
> Taking stock of and informing plant protection policy changes.
Eighteen organizations in 10 European countries are committed to ENDURE for four years (2007-2010), with financial support from the European Commission's Sixth Framework Programme, priority 5: Food Quality and Security.

Website and ENDURE Information Centre

www.endure-network.eu

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Leaflet 3: Non-chemical control of the western corn rootworm, *Diabrotica virgifera virgifera* in Europe

From Science to Field
Maize Case Study – Guide Number X

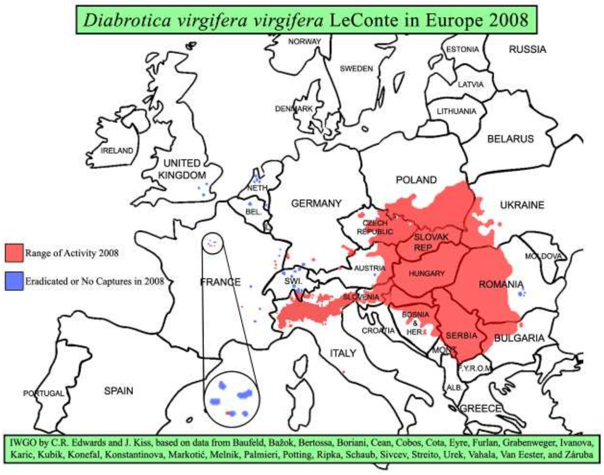
Non-chemical control of the western corn rootworm, *Diabrotica virgifera virgifera*, in Europe

Judit Papp Komáromi, J. Kiss and Z. Pálinkás
Plant Protection Institute
Szent István University
Gödöllő, Hungary

WCR in Europe

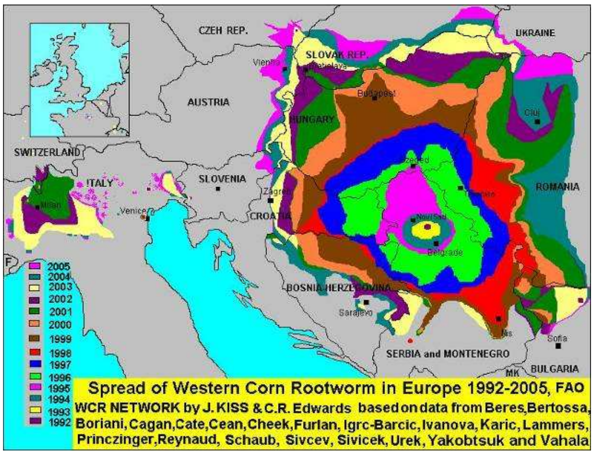
The western corn rootworm-WCR (*Diabrotica virgifera virgifera* LeConte) was first detected in Europe in 1992. The pest was found in a small continuous maize field near Belgrade International Airport, Yugoslavia (now: Serbia). On that field there were more than 10 beetles per plant, and first economic larval damage was visible. It is assumed that first beetles arrived to Serbia around the mid-1980s. Spreading of WCR across Europe is continuous. Plant lodging, economic larval damages were recorded in several countries (Serbia, Croatia, Romania, Slovakia, Czech Republic, Poland, Bulgaria, Hungary and Italy.

Beetles were detected from Ukraine to United Kingdom, from Germany to France, Italy (see spread map).


Diabrotica virgifera virgifera LeConte in Europe 2008

IWGO by C.R. Edwards and J. Kiss, based on data from Baufeld, Bažok, Bertossa, Boriani, Cean, Cobos, Cota, Eyre, Furlan, Grabenweger, Ivanova, Karic, Kubik, Konefal, Konstantinova, Markotić, Melnik, Palmieri, Potting, Ripka, Schaub, Sivcev, Streito, Urek, Vahala, Van Eester, and Záruba

Spread of WCR in Europe, 2008



Spread of Western Corn Rootworm in Europe 1992-2005, FAO
WCR NETWORK by J. KISS & C.R. Edwards based on data from Beres, Bertossa, Boriani, Cagan, Cate, Cean, Cheek, Furlan, Igrc-Barcic, Ivanova, Karic, Lammers, Princzinger, Reynaud, Schaub, Sivcev, Sivicek, Urek, Yakobtsuk and Vahala

Yearly spread of WCR between 1992 and 2005

What can we do with the new pest? First let us see its morphology, biology and possible control options.

Morphology of WCR

FAO/ J. Kiss

Adults of WCR are about 7.5 mm long and are shaped similar to cereal leaf beetle. WCR beetles are yellow in color. Three black strips run down the length of the wing covers and sometimes these converge and almost appear as a continuous black area. Normally the more continuous black area signifies males, but this is not always the case. The legs and antennae of the adults are black. The antennae of the males are always longer than the length of half on the beetle. In the case of females, the antennae will reach a maximum of 1/3 the length of the beetle.

Eggs are about 0.5 mm in size with whitish-yellow color. **Larvae** are whitish-yellow in color, with black head capsule. At the end of the abdomen there is a brownish dorsal plate. First instar larvae are 1.2 mm long, while third instar larvae can reach 1.5 cm length. **Pupae** (pupa libera) are whitish-yellow in color. Pupae are not moving in the soil, however if they are touched they start to waggle.

Life cycle of WCR

WCR is a leaf beetle (Chrysomelid) with one generation per year (univoltine). It overwinters in **egg** stage, in the soil of maize field. In the subsequent year, the first **larvae** hatch from middle May onwards (given dates are typical for Central Europe). There are three larval stages (L1, L2 and L3). Larvae are present from May through July till early September. Young (L1) WCR larvae are small and move among soil particles to find maize roots. Neonate larvae should find suitable root within 3 days. Larval development takes three weeks to complete. **Pupation** takes place in the soil and takes about one week. First **adults** emerge from the soil of the maize fields in late June to early July. The time of population peak of WCR adults varies from year to year and region to region. In most cases it comes from late July to early August. In some cases, WCR adult population peak occurs in late August or even beginning of September or in other cases in early July. Egg laying by WCR females starts from about middle July. Eggs are generally laid in 15-20 cm depth, in the soil. Adults are active in maize fields until autumn (first frosts).

Damage caused by WCR

Two development stages (larvae and adults) of WCR could cause **economic** damages, and only in **maize crop** stand. Significant damage occurs from larvae feeding. Larvae are feeding mainly on maize roots. When found, larvae start to feed on the hairy maize roots. The first and second instar larvae tunnel from root tips and can reach the plant base, leaving visible feeding scars. Third instar larvae generally feed on larger nodal roots near the plant stalk. Brace roots are often damaged once they enter the soil.

WCR adults feed on leaves, pollen, silks and young kernels and of maize plants (damage see later).

WCR feeding on other plants

WCR larvae can also feed and develop on the roots of some grassy weeds. Based on the literature there are 36 grassy weeds, on which WCR could finalize its development. However, in this case the mortality of larvae is high, thus the percentage of adults remains low. If neonate larvae are not able to find the suitable root within 3 days they would die, but survival to adulthood is significantly reduced if searching for food takes longer than 24 hours.

WCR adults feed on several grassy- and broad leaf crop species. There were 18 crop species counted except maize during gut content and pollen analyses of WCR adults in Hungary. Some pollens were from flowering weeds in maize field and some from other cultivated crops, as sunflower.

WCR damage in other crop stands?

Even though WCR larvae can develop and WCR adults can feed on other plants as maize, they COULD NOT cause damage on them.

WCR adult damage in first year maize?

Despite that adults feed on other plants as maize, they generally remain in the maize fields from where they emerged. In the case of inter field movements adults tend to immigrate in other maize fields for egg laying. Due to this simple behavioral habit WCR larval damage could appear only in maize after maize fields. However, negligible larval damage and lodging could appear in the field edge of first year maize field, if maize was cultivated in the neighboring field in previous year. However, there is **no economic larval damage** observed up to now (2009) **in first year maize** in Europe. There is no sign that crop rotation tolerant variant is present in Europe nowadays.

WCR larval damage

By feeding on the maize roots larvae could significantly damage or even to destroy the maize root system. Due to this damage crops will lodge and the typical “goose neck” symptom will appear. Crops are falling over in every direction in some parts of the field. This heterogeneity appears, since WCR adult, thus WCR egg population distribution is heterogeneous in the maize field. One could observe this damage outside from the field, that maize rows are rumpled, thus less noticeable.

Root damage by WCR larvae and subsequent plant lodging
SzIE/ N. Levay

How to identify WCR larval damage?

Lodged plants and/or rumpled rows are not obligatory symptoms caused by WCR larvae. Maize plants can lodge due to various reasons, such as:
- wind, especially in maize rows at the field edge;
- improper soil preparation;
- shallow root system due to environmental conditions;
- high plant density;
- mechanical damage to roots caused by cultivator;
- root/stalk damage caused by other pest.

Visual root observation is the best way to determine WCR larval damage. The intensity of larval damage could be measured by IOWA 1-6 scale, or by “node-injury scale.

WCR adult damage

Before the pollination WCR adults feed on maize leaves. Adults remove the epidermis in linear streaks similarly as cereal leaf beetle (*Lema melanopus*), or chew linear holes in leave tissue. Since adults prefer silk to leaves, during silking period adults tend to move to silk of maize. Adults can cause economic damage by clipping silks before or during pollination, since silk clipping can result in poorly filled ears. After pollination adults can feed on young, milky kernels of maize ear or on pollens which remains on maize leaves.

Community (EC) regulations for WCR in Europe

Western Corn Rootworm management regulations on European level are as follows:

- Council Directive 2000/29/EC of 8 May 2000 on protective measures against the introduction into the Community of organisms harmful to plants or plant products and against their spread within the Community;
- Commission Decision of 24 October 2003 on emergency measures to prevent the spread within the Community of *Diabrotica virgifera virgifera* LeConte (2003/766/EC);
- Commission Decision of 11 August 2006 “amending Decision 2003/766/EC on emergency measures to prevent the spread within the Community of *Diabrotica virgifera virgifera* LeConte” (2006/564/EC);
- Commission Recommendation of 11 August 2006 “on containment programmes to limit the further spread of *Diabrotica virgifera virgifera* LeConte in Community areas where its presence is confirmed” (2006/565/EC).

In these community regulations eradication, containment and suppression zones and measures are defined. Management regulations of Member States focusing on WCR management should fit under relevant community regulations.

Management of WCR in Europe

In Europe, in any region, at any population level the best and most secure WCR larval management is **crop rotation**.

In the regions where WCR is not yet present or WCR population is not yet established eradication and containment measures has to be obtained. In the case of observing any development stage of WCR or symptoms of WCR damage, contact national plant protection service. Plant protection service is aware of what measures have to be conducted in line with EU regulations.

In regions where WCR population is well established, suppression measures are relevant. In these regions WCR is a constant element of local agro-ecosystem, thus it has to be managed accordingly.

Management options at regions with well established WCR population level

First step of WCR management is that farmers, advisors should be aware of the presence of WCR adults or larvae on their fields or in their area. For detection and management purposes, several trap types are available. One of the trap types is the pheromone based trap that attracts male WCR adults. Often, pheromone is combined with floral lure and therefore both males and females are attracted to the trap. These traps are more sensitive for “early detection” of adults.

Visual traps (yellow colored traps) are also often used for population estimation purposes, thus less sensitive trap types but proper for management purposes.

Besides trap, visual counts (checking maize plant across the field during adult occurrence, specifically during pollination, silking) is also used by farmers and advisors for population estimation.

PAL trap for capturing male WCR adults

Pherocon AM trap sampling for male and female WCR

Primary management option of WCR is crop rotation. However, there are regions with well established WCR population, where crop rotation is not feasible due to some social-economic characteristics. In these regions continuous maize production is conducted on some fields. We should note, that continuous maize production does not mean automatically, that insecticide application has to be conducted. Larval damage for subsequent year can be estimated by WCR adult population sampling. Based on the row data of WCR population sampling risk management has to be conducted. In risk management regional characteristics, all abiotic and biotic elements of maize fields and social-economic aspects should be considered.

Cultural practices

The best and most suitable cultural practice to manage WCR is crop rotation. Any other cultural practices that enhance maize plant development (sowing time, ridging, selection of hybrid, irrigation, etc.) reduce or even neglect the need of insecticide application against WCR larvae. However, if WCR adult population was high (more than 1 beetle/plant in Central and Eastern Europe) in most of the cases these cultural options are not enough to manage WCR larvae.

Insecticide applications

Depending on member states different insecticides, with different active ingredients are authorized to control WCR.

WCR larval damage could be decreased by:
- insecticide seed treatment or,
- insecticide (in-furrow) soil application at sowing time or during first mechanical weed control.

Efficacy insecticide application against larvae depends on active ingredient of insecticide, insecticide formulation, climate, date of planting, date of rootworm hatch, etc. At high WCR larval population larval damage may appear even after seed treatment or soil insecticide application. Based on our present experiences in Central and Eastern Europe soil insecticide application reduces the WCR population in bigger rate. Never the less, seed treatment manages WCR larval population in suitable way, if larval population is low.
Insecticide application against adult population could have two aims:
- prevent silk from WCR adult clipping, thus to prevent yield loss or,

- to decrease WCR adult population in favor of decreasing next year larval population, thus root damage

Timing of foliar insecticide application is defined by the aim of it. To prevent yield in given year, application have to be done during silking period, before pollination, while to decrease larval population in subsequent year insecticide application has to be conducted during mass egg laying time of WCR females. However, abiotic circumstances may favor WCR larval development (good soil condition, proper wet conditions in soil, etc.) on way, that despite of foliar insecticide application larval damage could appear in subsequent year.

Foliar insecticide application can be conducted by:
- full rate dose insecticide or
- reduced rate insecticides with a feeding arrestant (stimulant)

Natural enemies

There are different natural enemies of WCR, such as entomopathogenic nematodes, fungi and predators in Europe. Such predators are grasshoppers, preying mantis, ground beetles, spiders, frogs and some birds. Based on our present knowledge, natural enemies could contribute in decreasing WCR population. Promising results have been achieved with entomopathogenic nematodes in field tests. Supporting available natural enemies of WCR and the natural regulating mechanisms in maize ecosystem belongs to the options of integrated management of WCR.

Transgenic maize hybrids

Various Bt transgenic maize hybrids, in which proteins against WCR larvae are expressed in the maize plant (including the root system) are widely used in USA. These hybrids are in authorization process in Europe.

11. Data sources

Hungary

Experts:	István Terpó, advisor (Tolna county)
	Zoltán Szabó, advisor and agronomist, Mezőhegyes Farm (Békés county)
	Andras Gellén, agronomist, Gellén Family Farm (Békés county)
	Zoltán Palinkas, agronomist, Szent István University, Gödöllő
	Jozsef Kiss, entomologist, IPM expert, Szent István University, Gödöllő
	Judit Papp Komaromi, entomologist, training and IPM expert, Szent István University, Gödöllő
	Zita Dorner, agronomist and weed specialist, Szent István University, Gödöllő
	Katalin Posta, microbiologist, Szent István University, Gödöllő
	Rita Bán, phytopathologist, Szent István University, Gödöllő
Publications:	Dömötör I., Kiss J., Szőcs G. (2007) First results on synchrony between seasonal pattern of pheromone trap captures of cotton bollworm, *Helicoverpa armigera* and appearance of freshly emerged larvae on developing cobs of corn hybrids. J. Pest Sci. 80:183–189
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	Szeőke K., Dulinafka G. (1987) Occurrence and damage of cotton bollworm in sweet corn (in Hungarian). Növényvédelem 23(10):433–438

Italy

Experts:	Vasileios P. Vasileiadis, agronomist-weed specialist, CNR-IBAF, Legnaro (PD)
	Stefan Otto, agronomist-weed specialist, CNR-IBAF, Legnaro (PD)
	Daniele Antichi, agronomist-weed specialist, SSSUP, Pisa (PI)
	Giorgio Casari, crop protection manager, Du Pont, Cologno (MI)
	Luigi Toppo and Claudio Campagna, crop managers, Syngenta
	Marco Pasti, president of the Maize Growers' Association, A.M.I., Venezia-Mestre (VE)
	Francesco Merlo, agronomist, La Veneta Agricola, Padova
	Lorenzo Furlan, agronomist-entomologist, University of Padova, Legnaro (PD)
	Marco Mazzoncini, agronomist-researcher, CIRAA-University of Pisa, San Piero a Grado (PI)
Institutions:	ARPAV (Regional Agency for Environment), www.arpa.veneto.it/meteo.htm and Padova University (temperature and precipitation)

Spain

Experts:	Pere Costafreda, technical Adviser, CUPASA, Lleida (fertilizer input, arthropod pests)
	Lluís Xanxo, agronomist and technical advisor, Cooperativa Pirenaica de La Seu d'Urgell. (fertilizer input, crop rotation)

Josep Piqué, agronomist, farmer and president of the Cooperativa del Camp Sant Gaietà, Almenar, Lleida (fertilizer input, arthropod pests)

Jaume Lloveras, agronomist, Department of Crop and Forest Sciences, Universitat de Lleida (fertilizer input, crop rotation)

Ramon Albajes, entomologist, Department of Crop and Forest Sciences, Universitat de Lleida (IPM)

Andreu Taberner, weed scientist, Departament d'Agricultura, Alimentació i Acció Rural, Generalitat de Catalunya and Universitat de Lleida (weeds)

Carlos Martin, technical advisor, Monsanto España (weeds)

Matilde Eizaguirre, entomologist, Department of Crop and Forest Sciences, Universitat de Lleida (arthropod pests)

Xavier Pons, entomologist. Department of Crop and Forest Sciences, Universitat de Lleida (arthropod pests)

Juan Pedro Marín, plant pathologist, Department of Crop and Forest Sciences. Universitat de Lleida (diseases)

Núria Sala, plant pathologist, Department of Food Technology, Universitat de Lleida (diseases)

Institutions: Xarxa agrometeorologica de Catalunya. http://xarxes.meteocat.com (temperature and precipitation)

Agencia Estatal de Meteorología. Ministerio de Medio Ambiente y Medio Rural y Marino, www.aemet.es/elclima/datosclimatologicos (temperature and precipitation)

Ministerio de Medio Ambiente y Medio Rural y Marino, www.mapa.es/estadistica/pags/publicaciones/BME/introduccion.htm (maize production area)

Departament d'Agricultura. Generalitat de Catalunya, www20.gencat.cat/DAR/Documents/Publications/Arxius/07dadbas.pdf (maize production types)

Publications: Sisquella M., Lloveras J., Alvaro J., Santiveri P., Cantero C. (2004) Técnicas de cultivo para la producción de maíz, trigo y alfalfa en regadíos del Valle del Ebro. Fundació Catalana de Cooperació. Lleida. 105 pp (fertilizer input, crop rotation and tillage)

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France

Experts: Sabine Battegay, ARVALIS, consultant (Normandie)

Joël Thierry, ARVALIS, consultant (Normandie)

Sylvie Renac, ARVALIS, consultant (Grand-Ouest)

Joël Thierry, ARVALIS, consultant (Grand-Ouest)

Sylvie Nicolier, ARVALIS, consultant (Southwest)

Guillaume Cloute, ARVALIS, consultant (Southwest)

Jean-Baptiste Thibord, ARVALIS, consultant (Southwest)

Jean-Paul Renoux, ARVALIS, consultant (maize in France)

Institutions: SCEES 2006, 2007, survey of farming practice, http://agreste.agriculture.gouv.fr/enquetes_3/pratiques_culturales_465/index.html (maize cropping characteristics, IPM, weeds, arthropod pests, diseases)

Meteofrance 1999-2008 (temperature and precipitation)

ARVALIS (temperature and precipitation)

The Netherlands

Experts: Jos Groten, researcher for variety testing of maize, Wageningen University (crop rotation, tillage, arthropod pests, diseases)

Rommie van der Weide, senior researcher for weed control and crop protection, Wageningen University (IPM, weeds)

Huub Schepers, phythopathologist, Wageningen University and Research Centre WUR PPO

Institutions: Het Koninklijk Nederlands Meteorologisch Instituut, http://www.knmi.nl/klimatologie/normalen1971-2000/per_station/stn260/4-normalen/260_debilt.pdf (temperature and precipitation)

Statistics Netherlands, http://statline.cbs.nl/StatWeb/publication/?VW=T&DM=SLNL&PA=3795mais&D1=a&D2=a&D3=a&D4=a&HD=080910-1557&HDR=T,G3&STB=G1,G2 (maize area and production types)

Agriholland, http://www.agriholland.nl/dossiers/bioland/home.html (weeds)

Wageningen University and Research Centre, Animal Sciences Group, www.handboeksnijmais.nl (arthropod pests, diseases)

Publications: Dewolf M., van den Klooster A. (2006) Kwantitatieve informatie akkerbouw en vollegrondsgroententeelt, PPO WageningenUR Publication 354 ISSN 1571-3059, Lelystad, The Netherlands, 286 pp. (fertilizer input)

Denmark

Experts:	Rolf Thostrup Poulsen, consultant, The Danish Agricultural Advisory Service (DAAS), Aarhus
	Ghita Cordsen Nielsen, entomologist and plant pathologist, The Danish Agricultural Advisory Service (DAAS), Aarhus
	Jens Erik Jensen, weed specialist, The Danish Agricultural Advisory Service (DAAS), Aarhus
	Bo Melander, weed scientist, University of Aarhus, Faculty of Agricultural Sciences, Research Centre Flakkebjerg, Slagelse
Institutions:	The Danish Meteorological Institute http://www.dmi.dk/dmi/index/danmark/klimanormaler.htm (temperature and precipitation data)
	Danish Environmental Protection Agency, official pesticide statistics (2006, 2007 and 2008) (herbicide use)
	The Danish Agricultural Advisory Service, the National Centre (2009) (all other data)

Germany

Experts:	Arndt Verschwele, weed scientist, Julius Kühn Institut, Federal Research Centre for Cultivated Plants, Institute for Plant Protection in Field Crops and Grassland, Braunschweig (weeds)
	Olaf Zimmermann, entomologist, Julius Kühn Institut, Federal Research Centre for Cultivated Plants, Institute for Biological Control, Darmstadt (arthropod pests)
	Elisabeth Oldenburg, phytopathologist, Julius Kühn Institut, Federal Research Centre for Cultivated Plants, Institute for Plant Protection in Field Crops and Grassland, Braunschweig (diseases)
	Udo Heimbach, entomologist, Julius Kühn Institut, Federal Research Centre for Cultivated Plants, Institute for Plant Protection in Field Crops and Grassland, Braunschweig (arthropod pests)
	Gustav-Adolf Langenbruch, entomologist, Julius Kühn Institut, Federal Research Centre for Cultivated Plants, Institute for Biological Control, Darmstadt (arthropod pests)
Institutions:	German maize association, www.dkm.de (maize cropping data)
	Landwirtschaftliches Technologiezentrum Augustenberg LTZ, http://www.landwirtschaft-bw.info/servlet/PB/menu/1034707_l1/index.html (maize cropping data)
Publications:	Mehrtens J.; Schulte M.; Hurle K. (2005) Unkrautflora in Mais – Ergebnisse eines Monitorings in Deutschland. Gesunde Pflanzen 57:206–218 (weeds)
	Rossberg D., Gutsche V., Enzian S., Wick M. (2002) Neptun 2000 – Erhebung von Daten zum tatsächlichen Einsatz chemischer Pflanzenschutzmittel im Ackerbau Deutschlands. BBA-Bericht Nr. 98 (weeds)

Poland

Experts:	Jozef Adamczyk, Smolice Breeding Company, IHAR Group, www.hrsmolice.pl (maize area, production types, IPM, weeds, arthropod pests, diseases)
	Artur Topolski, Kobierzyce Breeding Company, www.nasiona.com.pl (maize area, production types, IPM, weeds, arthropod pests, diseases)

Marek Mrówczyński, Plant Protection Institute, www.ior.poznan.pl (IPM, arthropod pests)

Roman Warzecha, Plant Breeding and Acclimatization Institute IHAR, www.ihar.edu.pl (maize production types, fertilizer, tillage, weeds)

Maciej Boroń, Plant Protection Institute, www.ior.poznan.pl (IPM, arthropod pests)

Paweł K. Bereś, Plant Protection Institute, www.ior.poznan.pl (IPM, arthropod pests)

Henryk Cygert, Smolice Breeding Company, IHAR Group, www.hrsmolice.pl (weeds)

Adam Paradowski, Plant Protection Institute, www.ior.poznan.pl (weeds)

Elzbieta Kochanska–Czembor, Plant Breeding and Acclimatization Institute – IHAR, www.ihar.edu.pl (diseases)

Piotr Ochodzki, Plant Breeding and Acclimatization Institute – IHAR, www.ihar.edu.pl (diseases)

Institutions: Instytut Meteaorologii i Gospodarki Wodnej, www.imgw.pl (temperature and precipitation)

Polish Central Statistical Office, www.stat.gov.pl (maize area)

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