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Pests, pesticide use and alternative options in European maize production: current status and future prospects

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Abstract

Political efforts are made in the European Union (EU) to reduce pesticide use and to increase the implementation of integrated pest management (IPM). Within the EU project ENDURE, research priorities on pesticide reduction are defined. Using maize, one of the most important crops in Europe, as a case study, we identified the most serious weeds, arthropod pests, and fungal diseases as well as classes and amounts of pesticides applied. Data for 11 European maize growing regions were collected from databases, publications and expert estimates. Silage maize dominates in northern Europe and grain production in central and southern Europe. Crop rotations range from continuous growing of maize over several years to well-planned rotation systems. Weeds, arthropod pests and fungal diseases cause economic losses in most regions, even though differences exist between northern countries and central and southern Europe. Several weed and arthropod 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 control including crop rotation, biological control, optimized application techniques for chemicals, and the development of more specific treatments. However, restrictions in the availability of alternative pest control measures, farm organization, and the training and knowledge of farmers need to be overcome before the adoption of environmentally friendly pest control strategies can reduce chemical pesticides in an economically competitive way. The complex of several problems that need to be tackled simultaneously and the link between different control measures 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 combined with pest monitoring programs may help to develop region-specific and sustainable strategies that are harmonized within a EU framework.

Introduction

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). The cropping area within the 27 member states of the European Union (EU) reached 8.3 million hectares in 2007 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). During the last 50 years, agricultural production has been increased dramatically because of the availability of high yielding varieties and synthetic fertilizers. In addition, the extensive use of chemical pesticides, which allowed farmers a better pest control, contributed substantially to the so-called 'green revolution' (Newsom 1980; Eichers 1981; Kogan 1998). However, the increased use of pesticides in agriculture resulted in adverse effects on human and animal health, environmental pollution (water and soil), and side effects on beneficial organisms including pollinators, decomposers and natural enemies (Metcalf 1986; Pimentel 2005). 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 and other highly effective crop protection methods often promote the development of pest resistance because they impose a high selection pressure on the pest populations (Metcalf 1986; Kogan 1998; Pimentel 2005). For example, more than 300 weed biotypes with resistance to herbicides are known, most of them from Europe and North America (De Prado and Franco 2004; Heap 2009).

Integrated production is a farming system that produces high quality food and other products while preserving and improving soil fertility and a diversified environment as well as respecting ethical and social criteria. Biological, technical and chemical methods are balanced carefully to minimize polluting inputs and to secure sustainable, yet profitable 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 harmful 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 the society while keeping chemical control of pests to a minimum (Huffaker and Smith 1980; Kogan 1986, 1998; El Titi 1992; Boller et al. 2004; European Parliament 2009). National and EU legislative directives have been imposed to limit pesticides and thus their negative impacts on the environment and human health (Thonke 1991; Lotz et al. 2002; Ackermann 2007). One of the most prominent examples for Europe is the unsustainable use of the herbicide atrazine, which has been banned in Germany and Italy since 1991 and in the remaining EU member states since 2005 (Ackermann 2007). Different initiatives from scientific organizations and policy makers in the EU have the aim of further reducing pesticides and of implementing integrated production in modern agriculture (Boller et al. 2004; Freier and Boller 2009).

Since 2007, the European Network for the Durable Exploitation of Crop Protection Strategies (ENDURE), comprising more than 300 European researchers, is committed to define crop protection strategies and research priorities to reduce the use of pesticides (http://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 (i) to give an overview of European maize cultivation practices,

(ii) to identify the status and development of most serious arthropod pests, weeds and fungal diseases in maize, (iii) to compile data on the classes and amounts of pesticides used and (iv) to discuss currently available options for pesticide reduction, potential long-term solutions, as well as their major restrictions.

Data Collection

Data were collected from 11 regions representing maize production all over Europe (fig. 1). Denmark and the Netherlands represented northern Europe. Southwest Poland, Southwest Germany and two Hungarian counties (Békés and Tolna) represented central Europe, and Italy (Po Valley region) and Spain (Ebro Valley region) the Mediterranean region. France with the regions Southwest, Grand-Ouest and Normandie represented western Europe.

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

In a workshop held in April 2008, a questionnaire template was built by representatives of the countries participating in this study. Thereafter, data on maize cultivation characteristics, important arthropod pests,

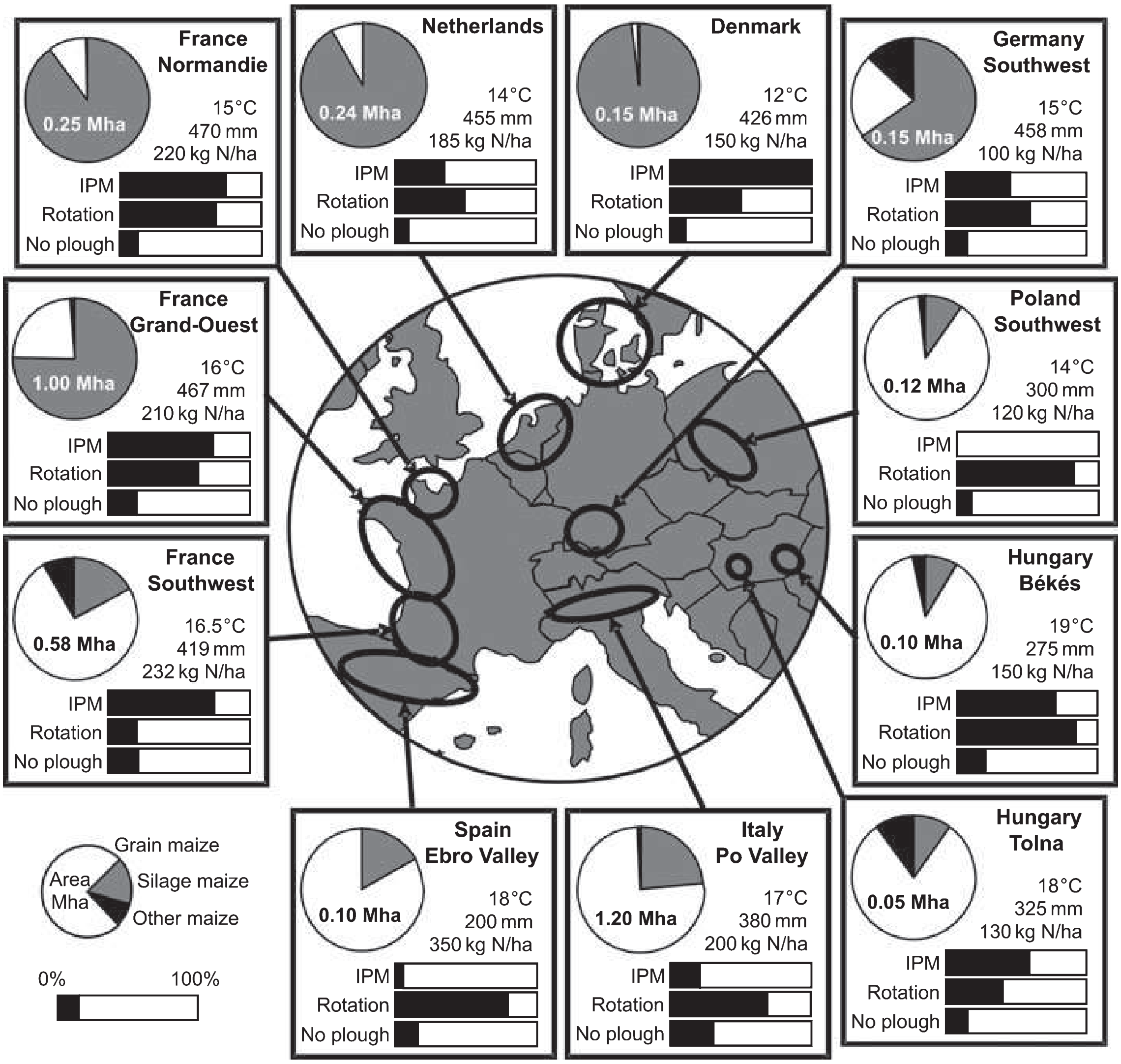


Fig. 1 Maize production characteristics in 11 regions in Europe. *Pie diagrams:* Maize production type: Silage (grey), grain (white) and other (black); *Numbers in diagrams*: total maize area in the region (in million hectares); *Numbers outside diagrams*: Average temperature (°C) and precipitation (mm) from April to October and fertilizers (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%.

weeds and fungal pathogens, as well as pesticide use were compiled by each partner and aggregated at the regional level. In the context of this paper, 'importance' is defined as potentially causing reductions in silage or grain quality or quantity in the absence of control measures. Published data, data from public and internal statistics as well as expert estimates were collected from regional, national and international sources. Data were 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 Supporting Information. In a workshop held in April 2009, data were evaluated, additional knowledge from invited experts was gathered, and options and restrictions for the reduction of chemical pesticides were discussed. Subsequently, data were verified, harmonized and completed by all authors.

Maize Cropping System in 11 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. 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. In general, the shorter and wetter climatic conditions in northwestern European regions were more suitable for silage maize, while grain maize production dominated in dryer and warmer regions of central and southern Europe (fig. 1). In addition to climatic conditions, regional needs for specific maize commodities, like on-farm use of silage for livestock-feeding, or the presence of agro-fuel or gas facilities, can influence the farmers' decision for production type.

The highest input of nitrogen fertilizers (organic and synthetic) was reported from the Ebro Valley (350 kg/ha), followed by France, the Po Valley 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 with 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 (<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% in Southwest France to 85% of the maize area in Southwest Poland and in Békés county. 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.

Guidelines for IPM exist in all covered regions, but the maize area, where those guidelines were applied, was highly variable. According to the definition by the International Organization for Biological and Integrated Control of Noxious Animals and Plants (IOBC), one fundamental principle of integrated production (and thus IPM) is that crop rotation is mandatory for arable crops including maize (Boller et al. 2004). However, definitions of IPM vary between countries and regions. Denmark, for example, 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 a harmonized definition of IPM is necessary before it can be promoted and implemented in a comparable way on a European level.

Weeds

Situation of weeds in Europe

More than 50 weed taxa were mentioned as being important in European maize production. The most important monocotyledonous weeds are Poaceae, such as *Echinochloa crus-galli* (L.) Beauv. and *Setaria viridis* (L.) Beauv. which cause problems in all European countries (fig. 2). While *Sorghum halepense* (L.) Pers. is a major weed in central and southern regions, *Elymus repens* (L.) Gould and *Poa annua* L. are important (even if less competitive) in northern regions. Furthermore, *Digitaria sanguinalis* (L.) Scop. and *Panicum* spp. cause problems in some regions.

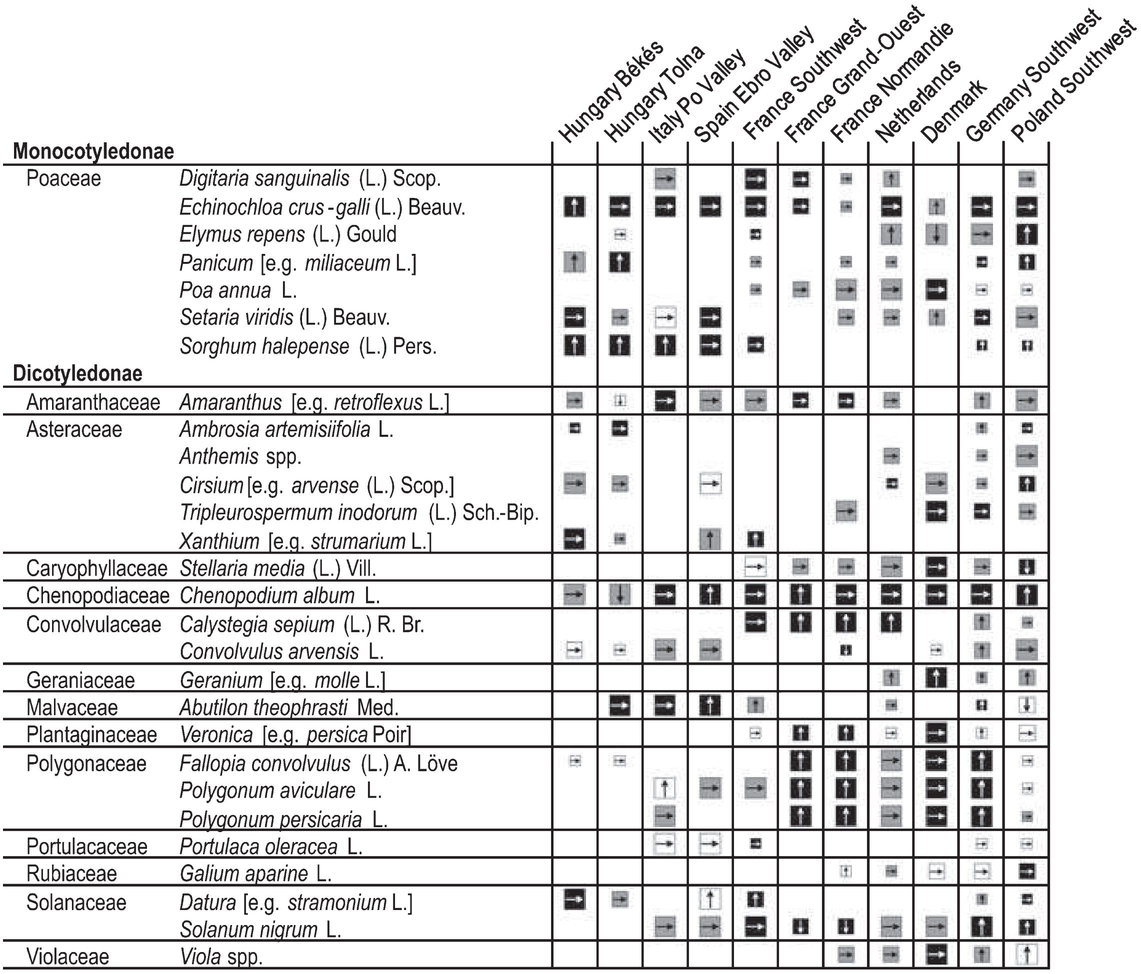


Fig. 2 Most important weeds in European maize production. Significance is represented by symbol colour: black = high, grey = medium, white = low. Occurrence is represented by symbol size: large = widespread and regularly, medium = widespread and occasionally, small = regionally and rare. The 5-year population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

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

In the northern regions, *Stellaria media* (L.) Vill. (Caryophyllaceae), *Calystegia sepium* (L.) R.Br. (Convolvulaceae), *Geranium* spp. (Geraniaceae), *Veronica* spp. (Plantaginaceae), *Galium aparine* L. (Rubiaceae) and *Viola* spp. (Violaceae) were reported to cause problems. In the central and southern regions, *Convolvulus arvensis* L. (Convolvulaceae), *Abutilon theophrasti* Med. (Malvaceae) and *Datura* spp. (especially *D. stramonium* L.) (Solanaceae) are significant weeds. Different genera 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, particularly late germinating and perennial weed species show increased importance. *Panicum* spp., *S. halepense*, *C. album*, *C. sepium*, *Geranium* spp. and Polygonaceae were reported to increase in three or more regions (fig. 2). Possible reasons may include change to herbicides with different spectra of activity, change to reduced tillage, seed transfer from set-aside areas and between fields by farm operations, and the application of seed-containing manure.

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 frequently 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 has been used in Europe, including ureas, triazine, pyridine, benzoylcyclohexanedione, amide, oxazole, aromatic acid and nitrile herbicides.

Options to reduce herbicide input

The aim of integrated weed management, a component of IPM, is to reduce herbicide input and failures of herbicides by controlling weeds non-chemically with 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).

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 a political program providing 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 maize emergence. The field is then cultivated mechanically, i.e. by harrowing, before sowing. Mechanical post-emergence weed control includes cultivation between rows (mainly hoeing and harrowing) and within rows (using finger-, torsion-, brush- or pneumatic weeders). Further options include flame weeding before or after emergence of maize and ridging later in the season (Melander et al. 2005; van der Schans et al. 2006; Cloutier et al. 2007; van der Weide et al. 2008). 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 damage to the crop (van der Weide et al. 2008).

Herbicide use 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 (Johnson and Hoverstad 2002; Dalley et al. 2004). Reduced weed pressure may also be achieved with cover cropping (Moonen and Bàrberi 2004; Melander et al. 2005), cleaning of machinery to avoid weed transfer between fields (Heijting et al. 2009), and in irrigated fields when irrigation is delayed (A. Taberner, personal communication). 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 in organic farming, purely mechanical and cultural methods are combined to replace labour intensive hand-weeding, in integrated farming

Table 1 Percentage of maize crop area treated with pesticides in 11 European regions and number of applications

	Herbicides[1]	Insecticides			Fungicides
Region	Spray[1]	Soil application	Seed treatment	On-plant spray[2]	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	20 (1)	100
Poland Southwest	100 (0.1/1.3)	0	20	20 (1)	100

[1] Number of applications pre-/ post-emergence in parenthesis.

[2] Number of applications in parenthesis.

systems, they can be applied in combination with herbicides to reduce the amount of active ingredient. Options include mechanical pre-emergence weed control followed by broadcast herbicide application with reduced doses that are sufficient for the small weed plants present at the time of application, as well as mechanical weed control between the rows and band spraying over the rows (Irla 1989; Baumann 1992; Pleasant et al. 1994; Buhler et al. 1995). 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. However, herbicide reductions may not be possible in the dryer Mediterranean regions, where highly competitive weed species are present. In tillage systems, without soil inversion (no ploughing), which provide improved soil quality and reduced erosion, the weed flora changes (Zanin et al. 1997; Bàrberi and Mazzoncini 2001) and often more herbicides are applied to avoid increased weed densities. 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 and García-Torres 1995; Berti and Zanin 1997; Masin et al. 2005, 2009; USDA 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 EU (EFSA 2009), the worldwide cultivation exceeded 30 million ha in 2008 (James 2008). Growing herbicide tolerant hybrids allows the adoption of a different spray regime, where a broad spectrum herbicide (e.g. glyphosate) can be applied post-emergence before the weed competition becomes too high. 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 and Barfoot 2008). Thus regional guidelines and decision support systems for farmers need to be available to achieve optimal environmental benefits (Kropff et al. 2008). Those should include resistance management strategies to delay the build-up of resistant weed populations.

Arthropod Pests

Situation of arthropod pests in Europe

At present, the most important arthropod pest of maize in Europe is the European corn borer, *Ostrinia nubilalis* (Hbn., Lepidoptera: Crambidae) (fig. 3). In the infested areas, *O. nubilalis* occurs 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* Lefèbvre (Lepidoptera: Noctuidae) causes additional economic damage (fig. 3). 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* Hbn.), which cause problems more in the central and southern countries (fig. 3). Among Coleoptera, wireworms (*Agriotes* spp., Elateridae) are reported to cause damage in all European regions included in this study. The western corn rootworm (*Diabrotica virgifera virgifera* LeConte), a chrysomelid beetle that is considered most destructive for maize production in the USA, caused economic damage in Hungary and other central and eastern European countries. Among the studied regions, populations of this pest have also established in Southwest Poland, Southwest Germany and the Po Valley. Economic damage remained low until 2007, but yield losses of about 2–3% were estimated at national level for Italy in 2009 (Informatore Fitopatologico 2009; M. Boriani and M. Agosti, personal communication). While damage is mainly caused by the larvae feeding on

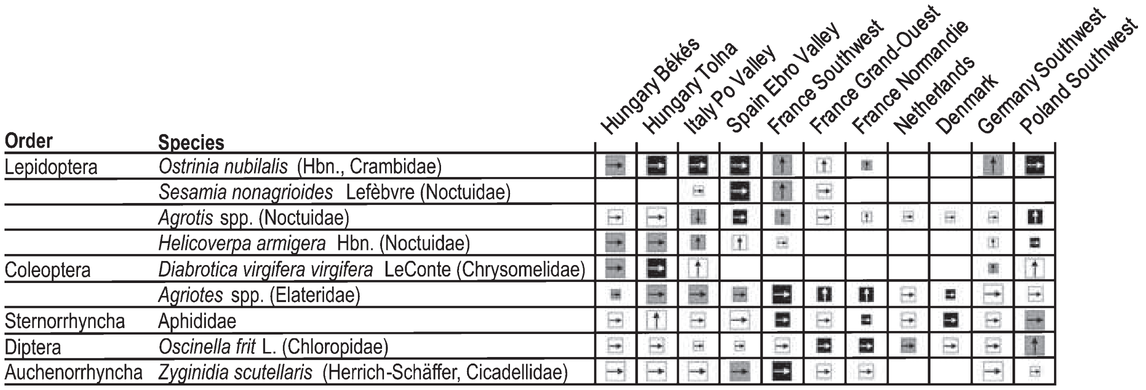


Fig. 3 Most important arthropod pests in European maize production. Significance is represented by symbol colour: black = high, grey = medium, white = low. Occurrence is represented by symbol size: large = widespread and regularly, medium = widespread and occasionally, small = regionally and rare. The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

roots, adults feeding on silk and ears may cause additional losses, particularly in maize production for grain, seed or food (sweet maize). Sap sucking pests, like aphids (Aphididae) and leafhoppers (Cicadellidae), as well as the frit fly (*Oscinella frit* L.) cause limited economic damage, despite being widespread and regularly occurring all over Europe (fig. 3). Other pests of regional importance include armyworms such as *Pseudaletia unipuncta* (Haworth, Lepidoptera: Noctuidae), Diptera species such as *Delia platura* (Meig.), *Geomyza* spp. and *Tipula* spp., Coleoptera species such as *Oulema melanopus* L., *Glischrochilus quadrisignatus* (Say), *Tanymecus dilaticollis* Gyll. and *Melolontha melolontha* L., spider mites (*Tetranychus* spp.) and thrips (Thysanoptera).

Within the last 5 years, problems with Lepidoptera pests including *S. nonagrioides*, *H. armigera* and *Agrotis* spp. were observed to increase (fig. 3). Maybe populations have been expanding because of warmer climatic conditions. With the increased cultivation of maize, *O. nubilalis* populations have been expanding since 1965 in central, northern and eastern Europe. *Diabrotica v. virgifera* was first detected in Europe in 1992 and has been invading the continent with an average rate of 40 km per year (Kiss et al. 2005; Meinke et al. 2009). Population management in infested areas as well as eradication programs in regions where populations have not been established, (e.g. in Southwest Germany, France and the UK) help to delay the spread of this pest. Other pest species remained fairly constant, even though increases may have occurred in some regions with favourable conditions (soil, rainfall, cropping sequence, etc.). One such example is the wireworm *Agriotes sordidus* Illiger, which increased in France (fig. 3).

Insecticide applications

Insecticides, delivered as seed treatments, soil insecticides or foliar applications were used in all European regions in maize (Table 1). While seeds were not insecticide-treated in France and Denmark, the total maize area where seeds were dressed with insecticides (e.g., thiamethoxam, tefluthrin, clothianidin) ranged from 20% in the Békés region and Southwest Poland to 100% in the Ebro Valley with the other regions in between. The maize area treated with soil insecticides was highest in France (32–42%) and Hungary (50–60%) (Table 1). At present, commonly used active ingredients in France and Hungary include tefluthrin and cypermethrin. In France, carbofuran, carbosulfan and benfuracarbe were used until 2009. The main targets of seed treatments and soil insecticides in most regions are wireworms. In Hungary, and in some areas in Italy, treatments were mainly applied against larvae of the western corn rootworm. In Southwest Germany, seeds were also treated against rootworm larvae in 2008 (U. Heimbach, personal communication). Because of improper coating and application techniques, however, insecticide dusts drifted to flowering trees and plants in the region, which lead to adverse effects on honey bees (Pistorius et al. 2009). Consequently, a temporary suspension of seed treatments was imposed in Germany and Italy. Seeds were also treated against sap sucking pests to prevent virus transmission, e.g. in the Ebro Valley.

Half of the maize area was treated with foliar insecticides in the Ebro Valley, followed by the Békés region, Southwest Germany, the Tolna region and Southwest Poland. No more than 11% of the area was treated in the Po Valley, France and Denmark. No insecticide sprays were applied in the Netherlands (Table 1). If treated, generally one application was done with the exception of 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 against western corn rootworm adults and *H. armigera* larvae (mainly in Hungary) as well as other pests listed in Table 1 were observed. The most commonly used active ingredients in spray insecticides were pyrethroids and organophosphates, but oxadiazine, nicotinoid, carbamate and diflubenzuron were also used.

Options to reduce insecticides

Biological control of *O. nubilalis* and *H. armigera* with *Trichogramma* spp. is one alternative to reduce insecticide applications. 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 per hectare for the first generation) are comparable to insecticides unless pest pressure is very high. 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). Research on more efficient *Trichogramma* spp. strains and other parasitoid species including larval parasitoids is underway to optimize European corn borer control (Wührer and Zimmermann 2007). Biological control may also become available for the control of the western corn rootworm. When applied to the soil early in the season, the efficacy of entomopathogenic nematodes was comparable with the soil insecticide tefluthrin and with clothianidin-coated seeds (Pilz et al. 2009). In the same study, the application of entomopathogenic fungi also reduced damage by rootworm larvae, but with lower efficacy compared with nematodes and insecticides. Even though biological control with pathogens is not of practical importance for European maize production at the moment, entomopathogenic fungi, viruses or *Bacillus thuringiensis* strains have potential to reduce chemical insecticides in the future. One example from Australia is a nucleopolyhedrovirus formulation, which has replaced chemical insecticides for the control of *Helicoverpa* spp. in a range of field crops, including maize (Buerger et al. 2007).

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 promoted with specific measures, including the establishment of a less intensively used and diverse crop pattern (Benton et al. 2003) and the management of field margins (e.g. flower strips and hedges to provide food and overwintering sites) (Kiss et al. 1993, 1997; Denys and Tscharntke 2002; Marshall and Moonen 2002; Bianchi et al. 2006).

Genetically modified maize producing insecticidal Cry proteins derived from *B. thuringiensis* (*Bt* maize) has been available for more than 10 years. In the EU, varieties expressing Cry1Ab protein for the control of corn borers were cultivated in seven 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, *Bt* maize hybrids expressing Cry3 proteins have been developed. While those hybrids are commercialized in the USA since 2003 (Hellmich et al. 2008), they are in the authorization process in the EU. Because of the high efficacy of the *Bt* proteins expressed in *Bt* maize hybrids, insecticides against the target pests are no longer needed. While non-target herbivores remain uncontrolled because of the high specificity of the *Bt* proteins, the complex of natural enemies also remains unharmed. Their biological control function is often sufficient to keep secondary pest populations 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 as a result of national bans of *Bt* maize in some countries, including Italy, France, Germany and Austria with high potential benefit for the environment and farmers' economy, (Brookes 2009).

Farmers have several cultural control options to reduce arthropod pest pressure. Crop rotation is highly effective against the western corn rootworm, because females lay their eggs mainly in maize fields, and the larvae hatching in the following year are largely restricted to maize roots as food. Additional cultural measures that contribute to reducing the damage of western corn rootworm larvae 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. Very late planting may also be an option, because most larvae have already hatched and starved. Against corn borers, mowing stalks and/or ploughing are methods used by farmers in most European regions to reduce numbers of overwintering larvae. Ploughing furthermore reduces populations of cutworms and potentially also wireworms. 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). 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 is a plant compound from watermelon which is highly preferred by rootworm adults to feed on. If applied together with insecticide as a foliar treatment, only small doses of active ingredient are necessary to kill the adults (Buhler et al. 1998; Edwards et al. 1999).

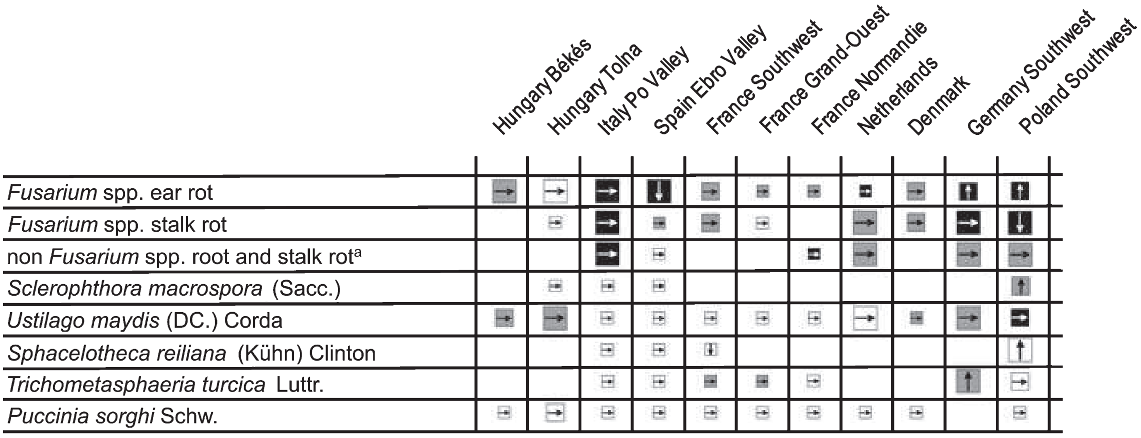
Similar to herbicides, insecticide input may be decreased by optimizing the currently used techniques. Calibration of sprayers may avoid the application of unnecessarily high doses. Scouting and threshold-based decision systems should ensure that insecticides are only applied when economic threshold 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; Komáromi et al. 2006), but predictions of 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).

Fungal Diseases

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* Schwabe, followed by *F. verticillioides* (Sacc.) Nirenberg, *F. proliferatum* (Matsush.) Nirenberg, and *F. culmorum* (Wm. G. Sm.) Sacc., depending on different climatic conditions. One major problem with *Fusarium* spp. is the production of mycotoxins, like fumonisins, trichothecenes (e.g., deoxynivalenol, nivalenol, T-2), and zearalenone, which lead to the contamination of human food and animal feed (Placinta et al. 1999; Logrieco et al. 2002; Bennett and Klich 2003; Munkvold 2003; Oldenburg and Ellner 2005). Depending on the ingested concentration, these toxins can cause acute or chronic toxic effects in humans or livestock, ranging widely from temporal feeding disturbances to serious damage of reproductive and digestive organs and even death (Placinta et al. 1999; Bennett and Klich 2003). This emphasizes the need for effective preventive strategies to minimize *Fusarium*-mycotoxin contamination of maize-based foodstuffs and animal feed (Aldred and Magan 2004). When the whole maize plant is used as silage feed for ruminants, all infected aboveground organs contribute to the contamination with mycotoxins (Oldenburg et al. 2005). However, ruminants show relatively low susceptibility to *Fusarium*-mycotoxins. In grain maize production, however, the plants are longer in the field, which can lead to the accumulation of higher mycotoxin concentrations. In addition, contamination is more critical than in silage maize, especially when grains are processed for human food or for feeding pigs, which show high sensitivity to the toxins. This has lead to the strict maximum levels for certain *Fusarium*-mycotoxins (deoxynivalenol, zearalenone and fumonisins) in foodstuffs (EC 2007) and the guidance values for animal feed (EC 2006) in the EU.

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* (Sacc.) Thirum., C.G. Shaw & Naras, *Sphacelotheca reiliana* (Kühn) Clinton,



[a] *Pythium* 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.

Trichometasphaeria turcica Luttr. (syn. *Helminthosporium turcicum*), *Ustilago maydis* (DC.) Corda and *Puccinia sorghi* Schw. may cause problems in some regions (fig. 4). In addition to *Fusarium* mycotoxins, aflatoxins (B1, B2, G1, G2) from *Aspergillus flavus* Link can cause problems in maize production, especially in the Po Valley.

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. This tendency is probably resulting from warmer climate and conservation tillage techniques combined with maize and wheat-dominated rotation systems increasingly practised in these regions. Residues of maize remaining on the soil surface promote the survival of fungal pathogens as well as that of European corn borer larvae, which may enhance the risk of ear infection with *Fusarium* spp. (Munkvold et al. 1997; Bakan et al. 2002). In Spain, ear rot has been decreasing in the recent years (fig. 4). This was most likely linked to the growing of *Bt* maize, which suffers less damage by corn borers and provides less opportunities for *Fusarium* spp. to enter and infect the plants (Bakan et al. 2002; Serra et al. 2008). Other fungal diseases remained fairly stable in the last 5 years.

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 for seed production in Southwest France against *Helminthosporium* spp., *Fusarium* spp. and *Puccinia* pp.

Options to reduce fungicides

Because options to protect maize against fungal diseases are limited, great effort has been made in the breeding of varieties with certain resistance (Snijder 1994). Official rankings of 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 and Munkvold 1999). In addition, many insects are known to transfer inoculum of fungal diseases between plants (Dowd 2003). Consequently, strategies to prevent feeding damage, including *Bt* maize, chemical insecticides and biological control with *Trichogramma* spp. can help to reduce fungal diseases and associated mycotoxin problems (Dowd 2003; Papst et al. 2005; Blandino et al. 2008a; Serra et al. 2008).

Fusarium spp. development is favoured by high levels of moisture during the maturation period of the crop (Lacey and Magan 1991). Options to reduce exposure to humid conditions, which occur frequently in autumn, include early planting (and consequently harvesting) of maize or the use of early maturing varieties (Blandino et al. 2008a, 2008b). In addition, early planting may result in reduced feeding damage by European corn borers, because 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 is cultivated at low plant densities, because of a less humid microclimate that limits fungal growth inside the crop (Blandino et al. 2008b). In dry areas, irrigation may reduce *Fusarium*-infection by improving plant fitness (Reid and Hamilton 1996; Reyneri et al. 2005). Furthermore, the type and amount of applied nitrogen-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. 2008c).

Cultural control measures to reduce the amount of initial inoculum of *Fusarium* spp. include crop rotation with non-host crops (no cereals) and ploughing of infested residues. In conservation tillage systems, varieties known to be less susceptible to fungal pathogens should be cultivated and maize residues should be chopped finely before being mulched to accelerate decomposition (Vogelgsang and Forrer 2006; Oldenburg et al. 2007).

A biological control system using an endophytic bacterium, *Bacillus subtilis*, showed promise for reducing mycotoxin accumulation during the endophytic growth phase of *F. verticillioides*. The inhibitory mechanism operates on the competitive exclusion principle, because this bacterium occupies the identical ecological niche within the plant (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 harvested grains. Model based approaches to predict disease incidence and mycotoxin contamination are available (Battilani et al. 2003, 2008; Samapundo et al. 2005, 2007). 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 pathogens' growth and spread, exists in Illinois, USA (Dowd 2005). However, no such software tool is used in European maize production.

Major Restrictions 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.

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. Field sizes and climatic conditions may be important factors. 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 control of corn borers 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. However, insecticides which are effective with this method need to be registered for foliar application in maize in the region of concern. 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 methods 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.

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 window of a few days 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, 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 an 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.

Farmers' knowledge and training

Farmers often perceive alternative pest management strategies and IPM concepts as complex, which limits their willingness to change farming practices. A transfer of knowledge and skills from research and development to farmers and consultants is thus needed for adoption on a commercial scale. Farmer–advisor–researcher partnerships (Karlen et al. 1995) and farmer participation in commercial field trials will most likely 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 (Komáromi et al. 2005).

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 for environmentally friendly methods or authorization rules might be required initially to overcome economic restrictions and to change farmers' choice and organization. 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 cooperation amongst farmers. Second, the new production system (production costs, yield, market price of maize and alternative crops) needs 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, new methods should efficiently control the pests of concern, not negatively affect crop growth, and not have a higher risk of failure, compared with previously used methods. Third, more time consuming methods result in increased costs for labour, especially if precise timing is needed, e.g. for mechanical weed control. In addition, costs for scouting of pest populations come with the adoption of IPM systems (Karlen et al. 1995; Brumfield et al. 2000).

Interactions of different strategies

For new pest 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 can lead 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 (Holland 2004), 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 (Bohanec et al. 2008; Sadok et al. 2008). Decision support systems in combination with monitoring programs may then help to decide which strategy is most appropriate under the current conditions in a specific region.

Conclusions and Outlook

Our survey revealed that maize production systems show differences in various European regions. While mainly silage maize is produced in the North, grain production dominates 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 regions, even though some differences exist particularly between the northern and southern regions.

Pesticides are currently the most common method to control weeds, arthropod pests and fungal diseases in European maize production. Nevertheless, several weeds and arthropod pests cause increasing problems, while decreases were reported only rarely (diseases remained fairly stable).

With the continuously high or even increasing traffic of humans and commodities, new introductions and the spread of arthropod pests, diseases, and to a lesser extent weeds, is likely to cause more problems in the future. In addition, warmer climatic conditions may lead to a further expansion of pest population boundaries. This illustrates that the goal of reducing pesticide applications is a big challenge, especially in southern and central Europe, where the pressure from highly competitive weeds and arthropod pests is higher than in northern countries.

Options to reduce the input of pesticides into the maize agro-ecosystem include the choice of varieties, cultural control measures, biological control, the optimization of application techniques of pesticides and the development of more specific and less toxic treatments. While some strategies need further development or more field research to 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 modified maize varieties. However, restrictions in availability, organization, and education and knowledge, need to be overcome before environmentally friendly pest control strategies can replace 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 cropping system. The fact that different control strategies, in particular cultural methods, may interfere with each other demonstrates that pest control needs to be seen in the context of the whole cropping system (including other crops in the rotation) and on a regional scale (Melander et al. 2005). If the cropping system comprises several crops and is able to counteract unfavourable conditions, pest control-failures in one crop with one specific method become less important.

In the EU, regulatory requirements for the sustainable use of pesticides will be in place presumably from 2014 (European Parliament, 2009). Each member state should adopt and promote a National Action Plan with quantitative objectives including IPM guidelines. This EU framework provides the opportunity for a certain harmonization of IPM across Europe which could result in agricultural products with more uniform standards of environmental impact and human health. While short-term consequences may be limited to the reduction of pesticide doses and the suspension of some harmful active ingredients, better education and training of advisors and farmers may lead to a more balanced, sustainable and truly integrated production in the long term. The compilation and analyses of pest problems, pesticide input and alternative options and restrictions provided in this study should provide a good basis for further discussion and development of advanced crop protection strategies with reduced input of chemical pesticides in European maize production.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1 List of experts, institutions and publications providing data on maize cropping characteristics, pests and pesticide use from the 11 regions of the maize case study.

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Supporting information

Pests, pesticide use and alternative options in European maize production: Current status and future prospects

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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)

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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)

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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)

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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)

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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)

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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)