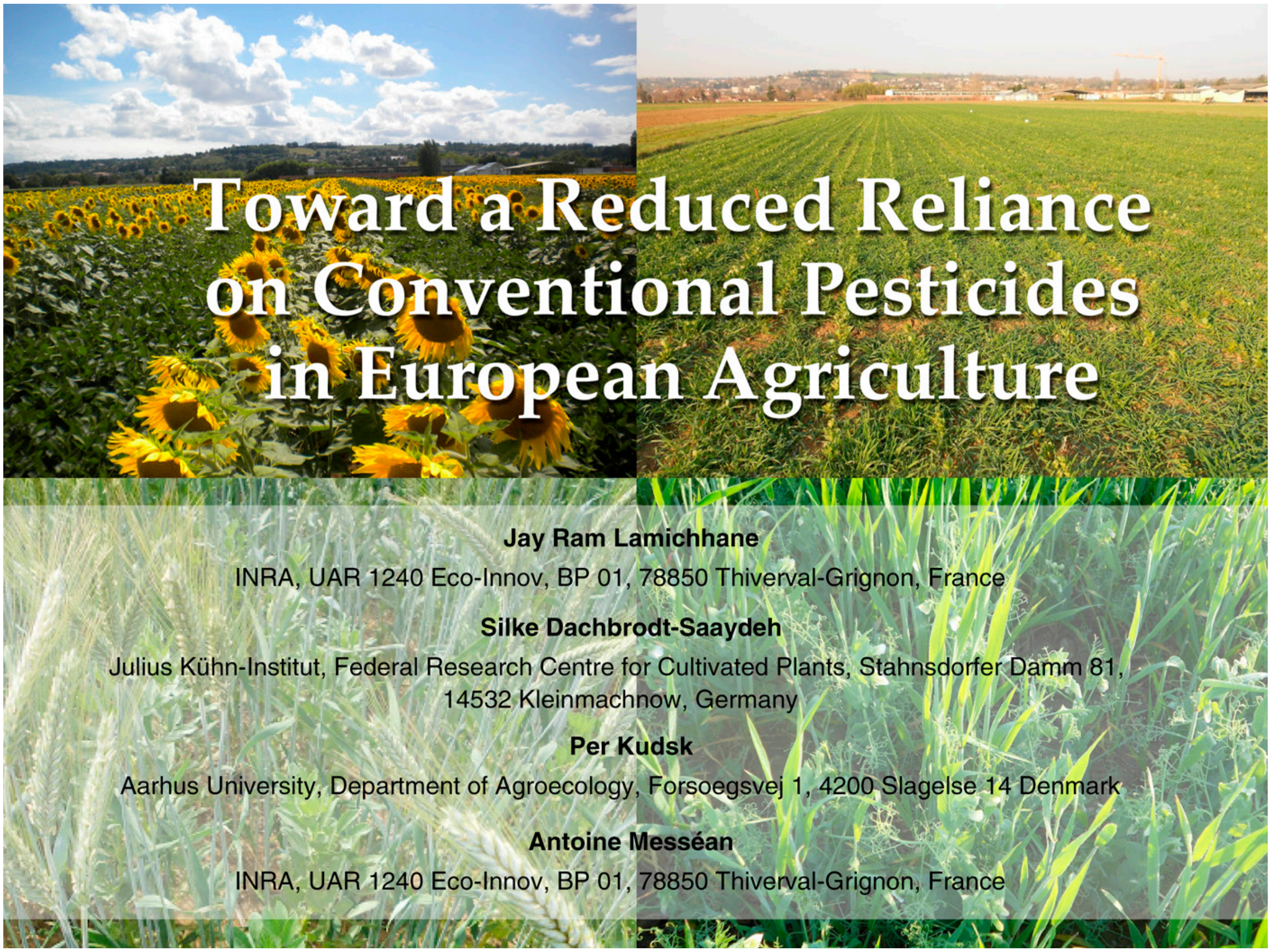

Toward a Reduced Reliance on Conventional Pesticides in European Agriculture

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Conventional Pesticides in Agriculture: Benefits Versus Risks

Conventional pesticides (i.e., only pesticides synthesized by the agrochemical companies and not those used for centuries, such as sulfur and copper) offer numerous benefits. Cooper and Dobson (2007) identified 26 primary (immediately apparent) and 31 secondary (noticeable in the long term or less intuitive) benefits of conventional pesticides. The most important benefits include increased crop yields, improved food safety, human health, and quality of life, and reduced labor, energy use, and environmental degradation (Cooper and Dobson 2007). For example, during the last four decades of the previous century, the average crop yields in agriculture have steadily increased (Oerke 2006). Much of the increase in yields per unit area could be attributed to more effective control of pests (pathogens, animal pests, and weeds) based on the use of conventional pesticides, rather than increases in yield potentials (Cassman 1999; Oerke 2006). However, agriculture in the 21st century faces the severe challenge of maintaining this trend of yield increases. Indeed, although yields continue to increase in some areas (Fig. 1), they are stagnating or declining in other parts of the globe (Ray et al. 2012).

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On the other hand, the use of conventional pesticides over the past five decades has led to a range of problems in agriculture, the environment, and human health (Geiger et al. 2010; Tegtmeier and Duffy 2004). In addition to the direct costs, there are numerous indirect or external costs derived from pesticide use. They include monitoring and sanitation for contamination of soils, drinking water, or food, poisoning of pesticide users and farm workers, and the deleterious effects on nontarget organisms such as bees and other beneficial insects, fish, and birds. Some of these costs are external to the specific decision maker and are usually absorbed by society. It is general knowledge that many pesticides cause harm to the environment and to human health. However, the calculation of the full external costs related to a pesticide and their varying formulations for individual applications is complex. Consequently, no estimation of such costs has been made at a practical level (Leach and Mumford 2008). A few studies from European countries have reported external costs of pesticide use in monetary terms. For example, external annual costs of pesticides for the United Kingdom and Germany amount to over 260 and 117 million Euros, respectively (Pretty et al. 2001; Waibel and Fleischer 1998). Other external costs of pesticides include a severe decline in the number of birds in the United Kingdom (Table 1) and a high percentage of workers poisoned by pesticides in Europe (Table 2).

The evolution of pesticide resistance among pest populations is another important factor driving a need to reduce our reliance on conventional pesticides. Only in the last decade, a large number of studies reported the evolution of resistance among various plant-pathogenic fungi and oomycetes to fungicide products (Table 3). In some cases, the same fungal pathogen developed resistance to dozens of fungicide products (Table 3). There are also reports of resistance evolution by bacterial pathogens to bactericides, including copper products (Canteros et al. 2008; Cazorla et al. 2002; Shenge et al. 2014). The development of resistance in weeds is another problem and blackgrass, in particular, is the most important herbicide-resistant weed in Europe (Moss et al. 2007). All these examples suggest that there is a need for a reduction and/or better use of resistance-prone, conventional pesticides in agriculture.

Development of Community-Wide Legislation in the EU: A Path Toward a Low Pesticide-Input Farming

Integrated pest management (IPM) has been defined as careful consideration of all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms and keep the use of plant protection products and other forms of intervention to levels that are economically and ecologically justified and reduce or minimize risks to human health and the environment (European Commission 2009). IPM emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems, and encourages natural mechanisms for pest management. For IPM professionals, this decision-based process involves coordinated use of multiple tactics (Box 1) for optimizing the management of all classes of pests in an ecologically responsible and an economically sound manner.

Increasing public concerns in Europe, due to negative consequences of pesticide use, have resulted in the development of a community-wide, harmonized legislation concerning the reduction of risks arising from the use of pesticides in the EU. This legislation is known as the EU Directive on Sustainable Use of Pesticides (2009/128/EC). Under this directive, the adoption of the eight general IPM principles (Barzman et al. 2015) are mandatory for all professional users of pesticides throughout the European member states from 1 January 2014 (European Commission 2009). However, the development and adoption of crop-specific IPM guidelines remains voluntary in Europe. This means that the member states are required to establish the framework(s) that will allow farmers to adopt IPM. The eight general IPM principles, however, offer a wide range of options available to member states to adopt the most suitable approaches for the development and implementation of IPM programs. This constitutes a new situation for farmers, retailers, and food companies that used IPM in the past to gain a competitive advantage in the market. Consequently, European (and world) agriculture is facing a gradual change in crop protection challenges, and this requires a concomitant change in thinking.

New Measures for a Better Assessment of the Adverse Impact of Pesticides

In order to assess the impact of EU policies on low pesticide input farming, it is necessary to develop tools to measure the use and adverse impact of pesticides. In most countries, pesticide use is simply estimated by collecting annual pesticide sales data and calculating pesticide use measured as kilograms of active ingredient per hectare (Table 4). It is widely recognized that such sales data provide no indication on the real pesticide use and the potential adverse effects as pesticides vary widely in their inherent toxicological properties and are used in doses from a few grams to several kilograms per

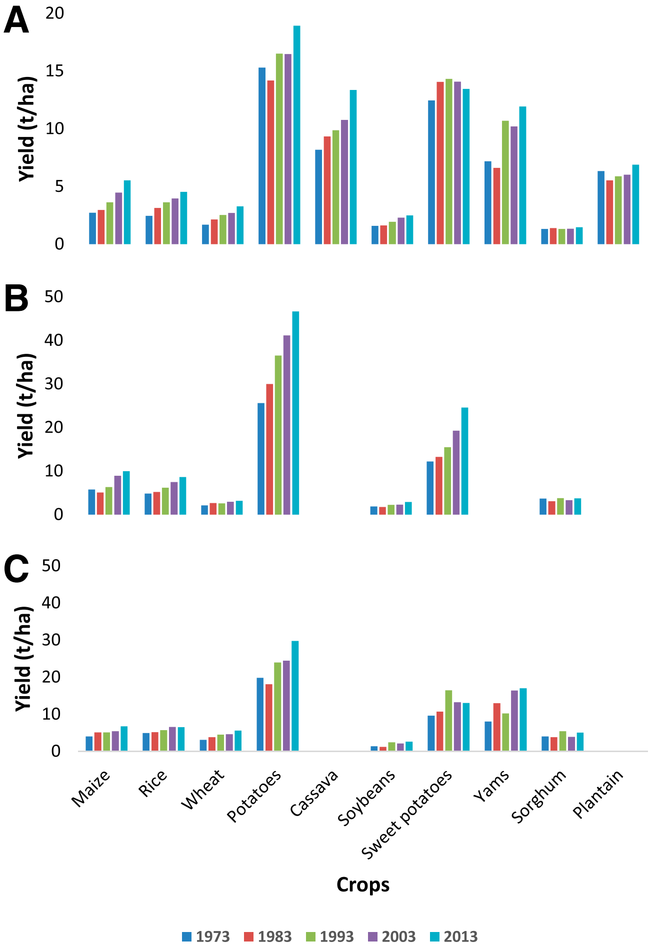

Fig. 1. Yield of the top 10 staples worldwide over the last 50 years (1973 to 2013) (Source: FAOSTAT). Global trend **(A)**, U.S. trend **(B)**, and E.U. trend **(C)**. Although a positive trend in terms of yield increase can be seen over the last 50 years, there have been strong fluctuations for some crops such as potatoes, sweet potatoes, and yams **(A and C)**, soybeans **(C)**, and sorghum **(A, B, and C)**. These fluctuations in crop yield can be associated with epidemics where pesticides were not effective or not available for use. Cassava and plantain are not grown in the United States or Europe and yams are grown only in Europe (the lacking histograms in B and C).

Table 1. Decline of birds due to pesticides in the United Kingdom (Campbell and Cooke 1997)

Species	Decline in number (%)[a]
Tree sparrows	89
Turtle doves	77
Bullfinches	76
Song thrushes	73
Lapwings	62
Reed buntings	61
Skylarks	58
Linnets	52
Swallows	43
Blackbirds	42
Starlings	23

[a] Data refers to the loss caused from 1967 to 1997.

Table 2. Percentage of workers poisoned by pesticides in Europe (PAN-UK 1997)

Poisoning[a]	Activities	Poisoning (%)[b]
Before usage	Handling of concentrates	6
	Application	39
	Preparation and mixing	28
	Total	**73**
After usage	Washing after use	12
	Use of contaminated equipment	7
	Handling of containers after use	2
	Working in areas previously treated	6
	Total	**27**

[a] Data are based on a survey of pesticide poisoning among the two million members of the European Federation of Agricultural Workers.

[b] These figures are from 1997 and therefore, advances in pesticide safety is expected since then, although no data are available.

hectare. Europe is the leading continent in terms of pesticides sales (Fig. 2). In EU countries such as Denmark, France, and Germany, pesticide use is now also measured as the treatment frequency index (TFI). TFI, introduced in Denmark in 1986, is defined as the number of pesticide applications per hectare per calendar year assuming the use of a standard dose for each authorized use (Kudsk and Jensen 2014). TFI is a measure of the number of pesticide applications and therefore solves the issue with different doses but does not take into account the differences in inherent properties and therefore cannot be used as a measure of reductions in the risk of pesticide use. This is why some EU countries are supplementing the TFI with other indicators. Denmark recently introduced the pesticide load indicator (PLI), which considers the amount of active ingredients (a.i.) in a pesticide and its inherent toxicity to human health and the environment and its fate in soil and water (Kudsk and Jensen 2014). In Germany, the model SYNOPS is used to obtain information on the potential risk for soil and water organisms. This model is being further developed to assess the potential impact of pesticide on beneficial organisms both at regional and national levels (Gutsche and Strassemeyer 2007). The EU itself, with Directive 2009/128/EC, is committed to develop and make available a set of harmonized risk indicators to the EU member states. These indicators shall help member states to identify trends in the use of certain active substances and identify crops, regions, or practices that require particular attention to further reduce the risks arising from pesticide use. A first step to this aim is the requirement by the Regulation 1185/2009/EEC, concerning statistics on pesticides in member states, to collect pesticide use data. EU member states collate the data in the most relevant crops according to their national action plans and report the quantities of active substances (Annex III, Reg. 1185/2009) applied for the individual crops per hectare. An example on the assessment of the use of active substances in winter wheat in Germany is shown in Figure 3.

The EU Pesticide Review Process and Focus on Nonchemical Tactics

A large number of previously available conventional pesticides have been banned and withdrawn from the EU market while marketing of several other pesticides is heavily restricted (Hillocks 2012). Such withdrawals and restrictions are due to Directive 91/414/EEC, which became effective in July 1993 (European Commission 1991).

Table 3. An incomplete list of reports of fungicide resistance evolution by plant-pathogenic fungi and oomycetes in the last decade

Pathogen	Resistance	References
Alternaria solani	Boscalid	Miles et al. 2013
	Penthiopyrad	Miles et al. 2013
Ascochyta rabiei	Pyraclostrobin	Delgado et al. 2012
Botrytis cinerea	Fenhexamid	De Miccolis Angelini et al. 2014
	Boscalid	De Miccolis Angelini et al. 2014
	Pyraclostrobin	Bardas et al. 2010
	Benomyl	Tanović and Ivanović 2010
	Benzimidazole	Banno et al. 2008
	Dicarboximide	Banno et al. 2008
	Thiophanate-methyl	Fernández-Ortuño et al. 2015
	Iprodione	Fernández-Ortuño et al. 2015
	Fludioxonil	Fernández-Ortuño et al. 2015
	Fluopyram	Amiri et al. 2014
	Fluxapyroxad	Amiri et al. 2014
	Penthiopyrad	Amiri et al. 2014
	Trifloxystrobin	Weber 2011
	Cyprodinil	Weber 2011
	Carbendazim	Sun et al. 2010
	Diethofencarb	Sun et al. 2010
	Procymidone	Sun et al. 2010
	Pyrimethanil	Sun et al. 2010
	Anilinopyrimidine	Myresiotis et al. 2007
	Phenylpyrrole	Myresiotis et al. 2007
	Hydroxyanilide	Myresiotis et al. 2007
Calonectria pauciramosa	Prochloraz	Guarnaccia et al. 2014
Cercospora kikuchii	Thiophanate methyl	Price et al. 2015
	Methyl benzimidazole carbamate	Price et al. 2015
Cercospora sojina	Quinone outside inhibitor	Standish et al. 2015
Colletotrichum cereale	Azoxystrobin	Young et al. 2010
Fusarium spp.	Fludioxonil	Gachango et al. 2011
Fusarium graminearum	Carbendazim	Chen and Zhou 2009
Fusicladium carpophilum	Azoxystrobin	Luo et al. 2013
Helminthosporium solani	Thia-bendazole	Geary et al. 2007
	Thiophanate-methyl	Geary et al. 2007
Microdochium nivale and *M. majus*	Strobilurin	Walker et al. 2009
Monilinia fructicola	Propiconazole	Brannen et al. 2005
	Methyl benzimidazole carbamate	Chen et al. 2013
	Demethylase inhibitor	Chen et al. 2013
Oculimacula acuformis and *O. yallundae*	Prothioconazole	Leroux et al. 2013
	Boscalid	Leroux et al. 2013
Penicillium digitatum	Fludioxonil	Kim, Saito, and Xiao 2015
Penicillium expansum	Pyrimethanil	Caiazzo, Kim, and Xiao 2014
	Pyrimethanil	Xiao, Kim, and Boal 2011
Peronospora belbahrii	Mefenoxam	Cohen et al. 2013
Peronophythora litchii	Carboxylic acid amide	Wang et al. 2010
Phytophthora capsici	Mefenoxam	Café-Filho and Ristaino 2008
Phytophthora infestans	Mefenoxam	Childers et al. 2015
Podosphaera fusca	Fenarimol	López-Ruiz et al. 2010
	Triadimenol	López-Ruiz et al. 2010
Podosphaera xanthii	Cyflufenamid	Pirondi et al. 2014
Sclerotinia homoeocarpa	Propiconazole	Jo et al. 2008
	Thiophanate-methyl	Jo et al. 2008
Sclerotinia sclerotiorum	Dimethachlon	Ma et al. 2009
Venturia inaequalis	Kresoxim-methyl	Chapman et al. 2011
	Dodine	Chapman et al. 2011
	Myclobutanil	Chapman et al. 2011
	Tthiophanate-methyl	Chapman et al. 2011
	Benzimidazole	Quello et al. 2010

The aim of this directive was to regulate the authorization of pesticides within the EU, but it also included a review of the almost 1,000 a.i. that were approved at the time when the directive went into force (Hillocks 2012). This pesticide review program has led to the withdrawal of 74% of a.i. used in pesticide products from the EU market (Fig. 4) in less than 20 years (1993 to 2010). Likewise, other key conventional pesticides are likely to be banned or heavily restricted following the implementation of Regulation 1107/2009/EC that went into effect in 2011, replacing Directive 91/414/EEC. This regulation introduced new criteria for authorization such as endocrine disrupting properties. The evolution in the pesticide review process has created a situation where European farmers are uncertain of which chemicals they can use now and which will be withdrawn in the near future.

The quantity of major conventional pesticides used in European agriculture has been variable in the last decade (Fig. 4). Despite several efforts, however, there has been no downward trend in their level of use. Fluctuations are, for example, due to different climatic conditions, which affect the occurrence of pests and thus the level of pesticide use. The reduced availability of some pesticides may have triggered the use of other pesticides in higher doses as substitutes. For example, the quantity of pesticides used (kg/ha) in Denmark decreased from 1981 to 2000 and then started to increase again (Fig. 5). This trend is further confirmed by the TFI values (Fig. 5). In Denmark, fluctuations in pesticide use have also been affected by changes in pesticide taxes or assumptions that specific a.i. will be banned or restricted. Similar situations are reported also in France, where the use of pesticides has relatively increased over the last several years (Fig. 6). Data from the German Network of Reference Farms illustrate variable pesticide use intensity in different crops and years (Freier et al. 2013). This underlines the limited explanatory power of overall figures and comparisons across European countries that only allow for very general information about trends.

The increasing or anticipated lack of available, conventional pesticides has led to a situation where European farmers now consider employing nonchemical tactics for pest management. However, for many crop/pest systems, no effective, economically feasible alternatives to conventional pesticides are available or under development (Lamichhane et al. 2015). Hence, there is a need to develop IPM strategies that significantly reduce reliance on the use of conventional pesticides while maintaining crop performance, yield, and profitability. On the other hand, a range of IPM methods are available, but need to be tailored to different climates, soils, and cropping and farming systems. Regional climate differences, disproportionate pest risks, and the varied effectiveness of IPM across European agroecosystems can result in significant loss of production in specific areas. This places EU agriculture at a disadvantage relative to other geopolitical regions and puts pressure on advances in research to foster and support IPM. Hence, ensuring stable crop yields and quality while reducing the reliance on pesticides is a challenge that research and the farming community are facing today.

IPM Versus a Zero Tolerance of Pesticides

The general public in EU member states perceives pesticides in general as a risk to their health. In particular, exposures via residues in freshly consumed fruit and vegetables are of major concern. Levels of pesticides in or on food produced in Europe are rarely above the maximum residue levels (MRLs), although such cases are sporadically reported from some EU member states (García-Reyes et al. 2008; González-Rodríguez et al. 2008). A recent report by the European Food Safety Authority (2015) stated that over 97% of food samples evaluated contain pesticide residue levels that fall below legal limits. About 55% of samples were free of detectable traces of pesticides. Despite this evidence and EU legislations that allow the sustainable use of pesticides, part of the public opinion regards any levels of pesticides in or on food as unacceptable. Whatever reductions are made in pesticide use will probably not satisfy those advocating "zero tolerance." This is not scientifically justified and such an approach may be counterproductive for the implementation of IPM. For example, some retail chains demand either zero pesticide residues in or on food or, for specific pesticides, contents considerably below the legal MRL thresholds. This not only affects the market and thus the farmer (e.g., a very high rate of rejection of agricultural products) but also drives legislation and damages agribusiness and the general economy.

Box 1. IPM tactics that can be combined for effective pest management.

Biological:
- Release of natural enemies (predators and parasitoids), use of bio-pesticides and bio-stimulants.

Chemical (as a last alternative):
- Use of conventional pesticides only when indispensable to prevent severe yield losses.

Cultural:
- Rotation, cover crops, mulching, intercropping, cultivar mixtures, false seedbed, selection of planting sites, trap crops, and adjusting the timing of planting or harvest.

Genetic:
- Use of pest-resistant plant varieties bred through conventional and/or genetically modified methods.

Mechanical:
- Mechanical and robotic weeding.

Physical:
- Use of barriers, row covers or trenches, traps, sticky boards or tapes, vacuuming, mowing or tillage, and hand picking of pests.

Table 4. Average use of pesticides from 2001 to 2012 in European countries. The quantity of pesticide used (kg/ha) is calculated by dividing the total quantity of pesticide used in a given country by the agricultural areas (Source: FAOSTAT).

	Pesticide usage (kg/ha)[a]				Pesticide usage (kg/ha)[b]			
Country	**FB[c]**	**H[d]**	**I[e]**	**Total**	**FB**	**H**	**I**	**Total**
Austria	1.08	1.08	0.09	2.25	0.48	0.48	0.04	1.00
Belgium	2.92	4.73	0.83	8.48	1.82	2.95	0.52	5.29
Cyprus	1.94	0.88	1.70	4.52	1.82	0.87	1.68	4.36
Czech Republic	0.36	0.88	0.06	1.30	0.27	0.67	0.05	0.99
Denmark	0.26	1.03	0.02	1.31	0.22	0.91	0.02	1.15
Estonia	0.07	0.55	0.02	0.63	0.04	0.38	0.01	0.44
Finland	0.09	0.57	0.01	0.67	0.09	0.56	0.01	0.66
France	1.98	1.35	0.10	3.43	1.31	0.89	0.07	2.27
Germany	0.79	1.37	0.10	2.26	0.56	0.98	0.07	1.61
Greece	1.28	0.67	0.65	2.59	0.58	0.30	0.29	1.17
Hungary	0.55	0.88	0.33	1.75	0.45	0.73	0.27	1.46
Ireland	0.50	1.73	0.04	2.27	0.13	0.45	0.01	0.59
Italy	4.82	0.92	1.16	6.90	3.35	0.64	0.81	4.80
Latvia	0.11	0.48	0.02	0.61	0.07	0.31	0.01	0.39
Lithuania	0.12	0.60	0.01	0.73	0.09	0.43	0.01	0.52
Netherlands	3.94	3.03	1.32	8.30	2.18	1.67	0.73	4.57
Poland	0.37	0.69	0.06	1.12	0.29	0.54	0.05	0.88
Portugal	5.59	0.98	0.21	6.78	3.08	0.54	0.12	3.73
Romania	0.23	0.40	0.11	0.74	0.15	0.27	0.07	0.50
Slovakia	0.23	0.71	0.05	0.99	0.17	0.50	0.04	0.70
Spain	0.74	0.61	0.73	2.08	0.46	0.37	0.45	1.28
Sweden	0.09	0.64	0.01	0.74	0.07	0.54	0.01	0.62
United Kingdom	0.93	2.47	0.20	3.60	0.32	0.85	0.07	1.24
Total	28.97	27.24	7.84	64.05	18.00	16.83	5.39	40.23
Average EU	**1.26**	**1.18**	**0.34**	**2.78**	**0.78**	**0.73**	**0.23**	**1.75**

[a] Arable land and permanent crops.
[b] Arable land, permanent crops, permanent meadows, and pastures.
[c] Fungicides and bactericides.
[d] Herbicides.
[e] Insecticides.

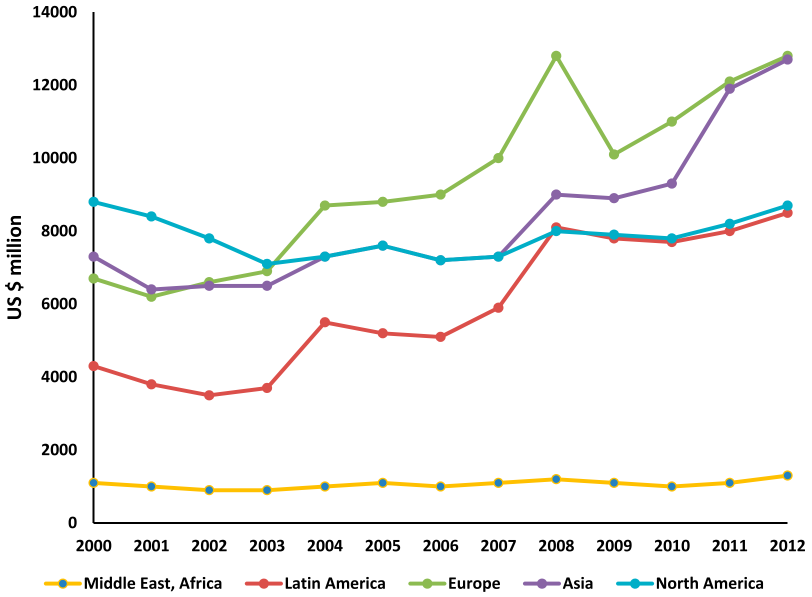

Fig. 2. Global pesticide sales data from 2000 to 2012 (Stockstad and Grullon 2013). Pesticides sales are increasing in Asia, Latin America, and Europe.

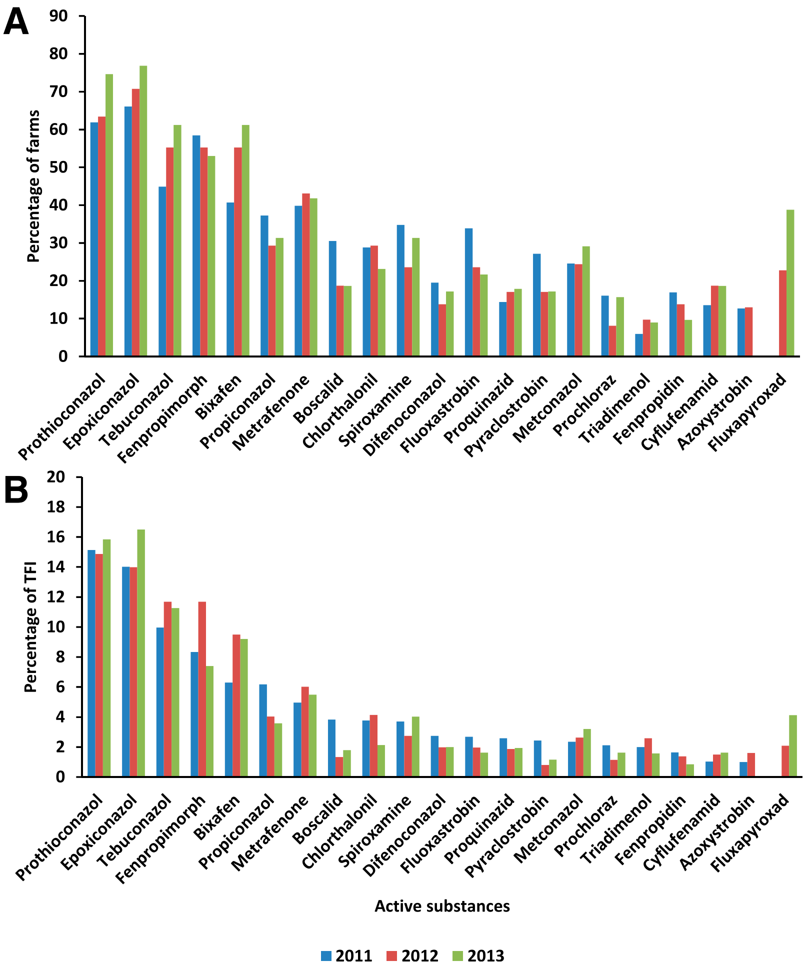

Fig. 3. Ranking of fungicide active substances used in winter wheat across the network of reference farms in Germany **(A)**. The ranking provides information on most frequently used fungicides in the farms but not on the potential risks of individual fungicides. Representation, expressed in percentage of each fungicide active substance on total TFI used in winter wheat in German reference farms **(B)**. The percentage of calculation for each individual active substance was based on the total fungicide TFI. Values are based on the data collected in 100 reference farms. The network of reference farms is a network of about 100 regular farms distributed all over Germany that volunteer to provide their anonymized pesticide use data for scientific purposes and the calculation of the necessary minimum of pesticide use.

The Role of Knowledge and Technological Improvements in Reducing Pesticide Use

Potential impacts of pesticide use reduction. Farmers rely on pesticides to protect their crops from pests. This reliance differs from one crop to another. There are, for example, cereal crops such as wheat for which different pesticides are available but have frequent overuse in some regions (see below). There are crops such as the so-called minor crops (Lamichhane et al. 2015) for which there is an acute lack of registered pesticides. Although the availability of pesticides for arable crops is justified by a high number of pests that threaten the viability of the production system, the quantity of pesticide used, measured as TFI, cannot always be justified. A telling example is pesticide use in wheat throughout some regions of France. A recent study, based on social, economic, and agronomic analyses, demonstrated that 33% of farmers use high levels of inputs to realize moderate yields, whereas 38% of farmers use moderate levels of inputs and realize high yields (Nave et al. 2013). This suggests that much still needs to be done in order to optimize the use of pesticides. Another recent study on winter wheat in eight European countries reported major differences in disease management and fungicide use patterns, with an average input equivalent of 2.3 applications per hectare per year (TFI) in the United Kingdom and 0.6 in Denmark (Jørgensen et al. 2014). These data suggest that the possibilities for a reduction of pesticide use across Europe depend, in part, upon cropping systems, climatic conditions, disease prevalence, and yield response of varieties to fungicide use.

Research shows that a drastic reduction in pesticide use, at least for cereal crops, would likely reduce yields significantly. Hossard et al. (2014) used a set of cropping systems experiments to quantify the yield losses resulting from a 50% reduction in pesticides use for winter wheat in France. The authors found that yield losses from a 50% reduction in pesticide use ranged from 5 to 13% of the yield obtained with the current pesticide use. A possible loss of the azole fungicides, due to Regulation 1107/2009/EC and its focus on endocrine disrupting properties, is expected to have a significantly negative impact on agricultural production in northern Europe. Without effective fungicide treatments, cereal production in Ireland would be economically unsustainable (Jess et al. 2014). A similar situation was hypothesized for other northern European countries (Blake et al. 2011; Di Tullion et al. 2012; Hillocks 2012). If the application of azoles were to cease in Europe, there would be a short-term reduction in wheat production of nearly 7% (9.8 million tons), which would increase to nearly 12% (18.6 million tons) by 2020 (Di Tullion et al. 2012; Jess et al. 2014). This drop in production would lead to a relative economic loss of 2.4 billion Euros in the short term, and 4.6 billion Euros by 2020. This compromises Europe's ability to be agriculturally self-sufficient and remain competitive in the global wheat market. Consequently, under current production conditions, sustainable food production and food availability in general could become important issues for the entire community.

The use of pesticides can be markedly reduced without any concomitant economic losses if optimal IPM tactics are incorporated. Results from German long-term experiments (1997 to 2007), based on a 50% reduction rate of pesticides in cereal crops, showed that economic benefits due to fungicide applications was only gained in years with high infestation levels. A fungicide-related yield increase was obtained only in 7 and 6 out of 10 years in winter rye and winter barley, respectively. In both cereals, the yield and economic benefits of the 50% dose rate variant were about half of the situation related treatment scheme. Interestingly, those results were not confirmed in winter wheat in the same trial. In the latter case, significant yield and economic benefits were only achieved in 3 years and the 50% reduction performed better than the situation related schemes. That was

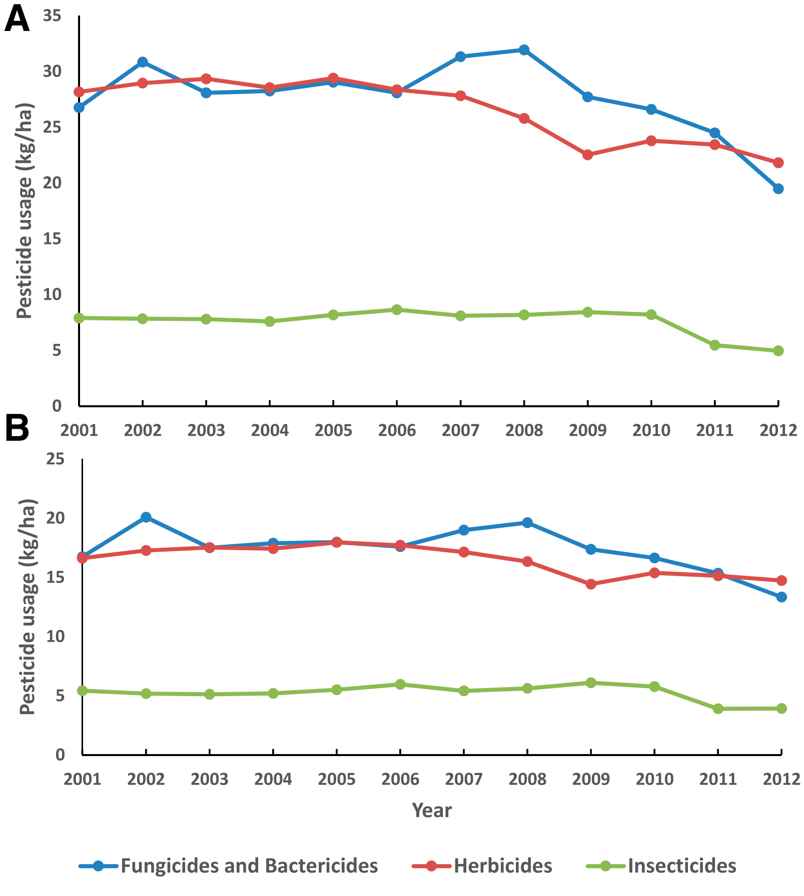

Fig. 4. Trend in the use of pesticide (kg/ha) in European arable land and permanent crops **(A)**, and in arable land, permanent crops, permanent meadows, and pastures **(B)** from 2001 to 2012. No complete data are available in the use of pesticide after 2012 (Source: FAOSTAT).

especially true in those years when infestation levels were above the treatment thresholds but remained moderate throughout the season. This was attributed to the selection and use of highly resistant crop varieties (Jahn et al. 2010). This example points out the role of prevention, i.e., variety choice, the adaptation of treatment schemes according to the resistance of varieties, and role of optimized timing of pesticide applications.

The use of effective pesticide sprayers and nozzles is important to reduce pesticide drifts. Significant amounts of pesticides are often placed in the nontarget environment during the application process. Hence, control or minimization of drift, especially while treating in orchards (where elevated plant height renders treatment difficult), must be considered. For example, to optimize the use of pesticides, there are several innovative nozzles available and farmers can improve pesticide application efficiency by careful selection of spray nozzles to minimize drift (e.g., air induction nozzles) and improve spray retention (e.g., angled nozzles) (Fig. 7).

Adoption of Systems, New Technologies, and the Role of Knowledge

Innovative cropping systems. The term ‘cropping system’ refers to the crops, crop sequences, and the management techniques used on a particular field over a period of years. The adoption of innovative cropping systems (Table 5) may reduce the reliance on conventional pesticides in the long term. Adapting current high-input agriculture and using an agro-ecological approach can achieve this. The main pillar of this approach is the conservation or introduction of plant diversity in agroecosystems. In particular, deploying a number of different plant species within the same production system (Figs. 8 and 9) can reduce the impact of pest and diseases in a number of ways (Ratnadass et al. 2012). Such systems must be targeted to deeply modify the current management scheme that focuses on the control of a single pest present on a specific crop during a single season (one pest, one crop, and one year) to multipest systems and systems applied at landscape level (Meynard et al. 2013). Overall, the successful application of such systems is influenced by cost effectiveness, market access of the commodities, and farmers’ attitudes to adopt such innovative cropping systems. These systems generally benefit from the integration of a range of approaches such as deployment of resistant/tolerant cultivars to pests, long rotations, early detection methods, pest/disease forecasting models, and precision spraying. However, the acceptance of such systems by farmers will depend on yields, perceived risk to management, individual management capabilities, and environmental interactions that influence the economic viability of the cropping system. For this reason, incentives that encourage growers to adopt these practices might be particularly important while striving for a reduced reliance on conventional pesticides.

In France, a joint network of farmers has gathered 59 innovative cropping systems that are assessed into 33 different experimental sites (Reau et al. 2010). Most of the innovative cropping systems are based on multicrop rotations, with alternation of plowing and

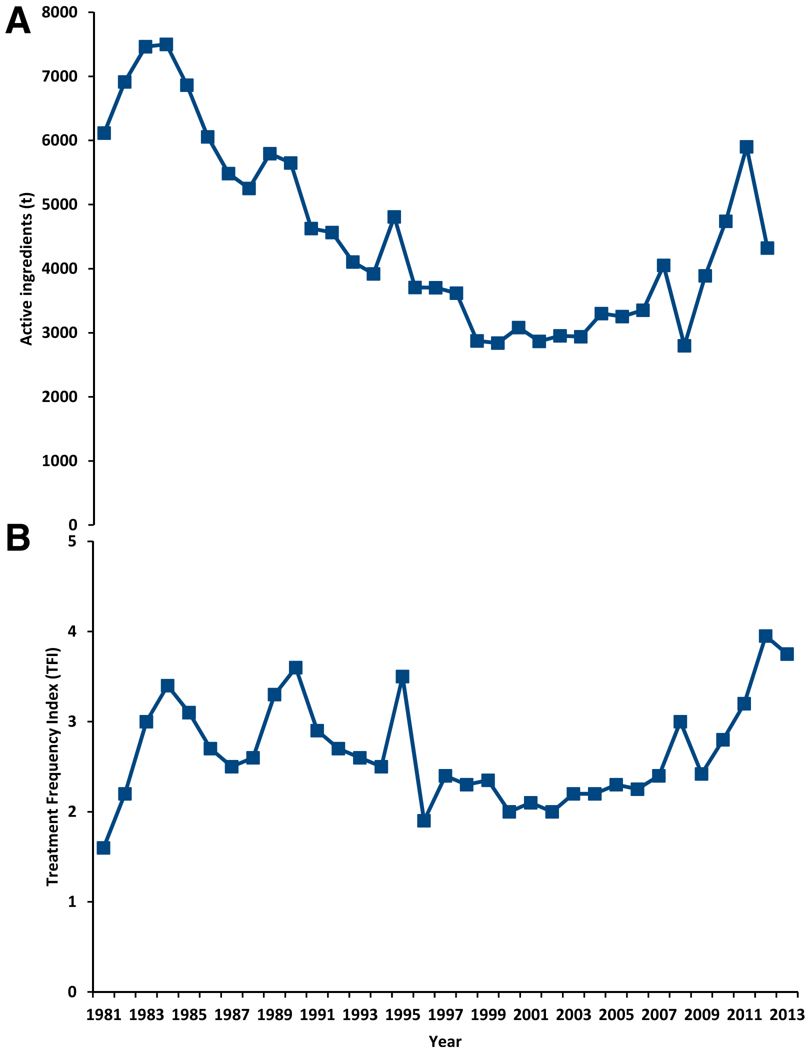

Fig. 5. Trend that shows the quantity of active ingredients used **(A)** and treatment frequency index **(B)** in Danish agriculture from 1981 to 2013. Despite significant variations over the years, the overall trend was a reduction in pesticide use until 2001, but since then pesticide use has increased.

non-inversion tillage, and low input crop managements. In Picardy (northern Paris basin), eight farmers have experimented with "integrated crop production." After 5 years of collective learning, their mean TFI was markedly decreased (3.4 compared with 4.4 before practicing such systems while the mean reference TFI of the Picardy region was about 5.8) and the trend in their net income was positive in comparison with the other farms in the region. However, the authors did not report which of these cropping systems were most effective toward reducing TFI.

Recently, Pelzer and coworkers (2012) proposed a multi-attribute model to perform ex-ante assessments of the sustainability of innovative IPM. The authors studied two arable cropping systems, winter wheat-based and corn-based systems, and found differences between them. Economic sustainability for the winter wheat-based system was slightly lower for the IPM-based cropping system compared with the high-input conventional system. Lower economic sustainability was mainly due to higher labor costs (because of superficial tillage and frequent crop monitoring). However, systematic field observations for the monitoring of pests and treatment decisions based on thresholds helped limit pesticide use to the actual minimal required level. By contrast, for the corn-based system, the economic sustainability improved with the innovative IPM system compared with the conventional system. This result was mainly due to the reduced production costs (lower costs for pesticides, fertilizers, and irrigation) and higher yields. Similar observations on ex-ante evaluation of more innovative IPM strategies for corn-based cropping systems have also been reported by another study based on experts' interviews throughout European countries (Vasileiadis et al. 2011).

Bio-pesticides, bio-stimulants, and biocontrol. The use of bio-pesticides in crop protection can lead to decreased levels of pesticide residues in foods, resulting in lower risk for the consumer. However, the approval and registration of bio-pesticides in the EU have been facing several problems due to the application of the same registration criteria used for conventional pesticides (Chandler et al. 2011; Czaja et al. 2015). In addition, although shifts from the use of "old" and highly persistent conventional pesticides to bio-pesticides should improve the situation in many countries of the world, they are still problematic. Even the latest generation of bio-pesticides could pose problems for wildlife, perhaps not directly by receptor interaction in nontarget species, but indirectly by impairing species interactions (Köhler and Triebskorn 2013), although the underlying mechanism is not yet clear.

Plant bio-stimulants can be defined as substances and materials which—when applied to plant, seeds, or growing substrates in specific formulations—have the capacity to modify physiological processes of plants in a way that provides potential benefits to growth, development, and/or stress response (du Jardin 2012). In this way, the use of bio-stimulants can lead to a reduced reliance on conventional pesticides (Calvo et al. 2014). However, the definition and concept of plant bio-stimulants is still evolving, which reflects the diversity of materials that can function as bio-stimulants (Calvo et al. 2014). The EU legislation describes only two categories of products applied on plants: fertilizers (nutrients) and plant protection products (pesticides). Bio-stimulants have no direct action against pests, and therefore do not fall within the regulatory framework of pesticides (European Biostimulants Industry Council 2012a). Bio-stimulants operate through different mechanisms than fertilizers, regardless of the presence of nutrients in the products (European Biostimulants Industry Council 2012b). Due to multiple functions/effects of bio-stimulants on plants, for instance, it is not clear whether or not the EU legislation, in the future, will consider bio-stimulants as a separate category of products than bio-pesticides or fertilizers.

The use of biocontrol agents in weed control has been reported from several parts of the world including Africa (Nemat Alla et al. 2008; Zahran et al. 2008), Asia (Siddiqui et al. 2010), Europe (Gerber et al. 2011; Muller-Scharer et al. 2000), and North (Smith et al. 2006; Winder 1999) and South (Ellison and Barreto 2004) America. In addition to controlling endemic weeds, several biocontrol agents can manage invasive weed species. A recent example is the first release of a classical fungal biocontrol agent, *Puccinia komarovii* var. *glanduliferae*, against an invasive alien weed, *Impatiens glandulifera*, in Europe (Tanner et al. 2015). There are similar reports on the release of fungal biocontrol agents to control invasive weeds outside Europe (Ellison et al. 2006, 2008). Therefore, there are prospects for sustainable management of several problematic weeds across the globe.

The effectiveness of biocontrol agents, especially those of fungal isolates, often depends on formulation (Boyette and Hoagland 2013) and the climatic conditions (Smith et al. 2006) that represent a severe constraint for weed biocontrol. In addition, most pathogens of weeds are not useful in their wild form because they are not sufficiently host-specific and/or virulent. To overcome this problem, Sands and Pilgeram (2009) suggested that exploiting the inhibitory effects of certain amino acids on the growth and development of specific plants could be an effective way to enhance weed biocontrol. Pathogens that overproduce these selected amino acids can be selected from a pool of spontaneous mutants. Such mutants can have increased pathogenicity to their target weed and enhanced field performance as biocontrol agents. Indeed, enhancement of biocontrol efficacy in three, separate pathogen-host systems—two with *Fusarium* and one with *Pseudomonas*—has already been reported (Tiourebaev et al. 2000). Hence, the same technology can be used to obtain enhanced biocontrol

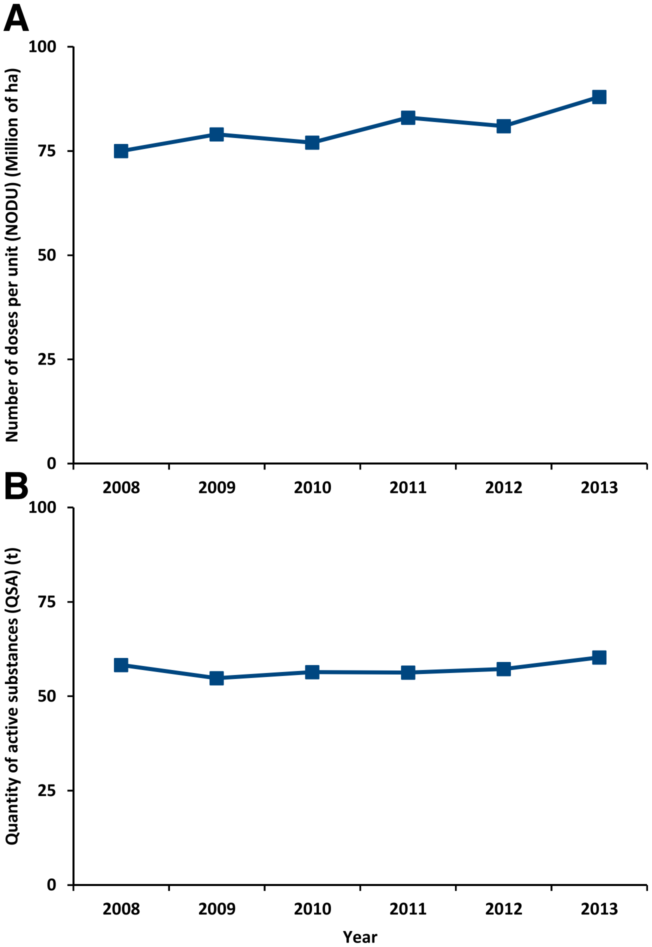

Fig. 6. Trend that shows the evolution of pesticide use in French agriculture from 2008 to 2013. The number of unit doses (NODU) is an all-crops indicator calculated annually from pesticide sales data transmitted by secondary distributors in the context of the statement under the royalty for diffuse pollution **(A)**. The quantity of active substances (QSA) indicator **(B)** is an indicator expressed in kilograms of active substances. This indicator is simple to understand and easy to calculate, but it is an amalgam of effective doses of different active substances, ranging from several kilograms per hectare, such as mineral fungicides, to a few grams per hectare. However, new substances effective at lower doses may substitute a pesticide active at a higher dosage. To overcome this, the NODU reports the amount of each active substance in a dose "unit" that is clean and allows it to assess the intensity of pesticide use independently of possible substitutions of the active substances with new substances effective in lower doses. It allows a better understanding of the evolution of agricultural practices.

agents capable of producing inhibitory levels of selected amino acids in situ. Finally, synergistic effects by mixing biocontrol agents and herbicide doses, slowing down the growth of weed plants, have been observed, which can be another potential approach to reduce the use of pesticides (Peng and Byer 2005).

Integration of Biotechnology Into IPM

Important advances are occurring in science and need to be considered for integration into the IPM framework. More precise breeding techniques, such as marker-assisted selection for the genetic improvement of plants, could expedite the transfer of traits such as resilience and resistance. Although there is not a consistent definition of resilience (Doring et al. 2015), we define resilience as the capacity of an organism to respond to a disturbance by resisting biotic and abiotic damage and recovering quickly. Resilience differs from resistance, which is the capacity of an organism to prevent pest attacks and/or reduce their populations associated with it.

Advances made for recent technologies and the available knowledge of the plant immune system might be a basis to engineer plant disease resistance (Dangl et al. 2013). The use of resistant plants to manage pests is the most effective tool for pest management from economic and environmental perspectives. However, a primary paradox is that widespread use of such cultivars is hindered, as the number of cultivars that possess high levels of resistance to key pests is very limited and the resistance traits in question are mostly aligned with a yield penalty. This is mainly because highly resistant cultivars to a given pest may be markedly susceptible to another pest. Therefore, there is need for future research to breed varieties that are resistant to more than one pest and ensure high and stable yields.

Genetically modified (GM) crops offer a potential to contribute to the establishment of sustainable crop protection systems only when they are carefully integrated within the framework of IPM, rather than applied as “a stand-alone pest control measure.” Insect-resistant GM crops are proving to be safe, effective, and amenable to insect suppression tools that are compatible with other IPM tactics, including cultural and chemical controls and the conservation of natural enemies as important agents of biological control (Lu et al. 2012). Globally, the high level of adoption of *Bacillus thuringiensis* toxin genes (Bt) in cotton having more than one trait has drastically reduced the need for insecticide sprays against bollworm larvae *Helicoverpa armigera* (Cattaneo et al. 2006; Shelton et al. 2002; Tabashnik et al. 2010). Arthropod natural enemies that provide biological control of pests are enhanced by the absence of broad-spectrum insecticides, which results in a positive effect in the whole agricultural landscape (Lu et al. 2012). However, experience in Bt cotton has shown the potential for reductions in insecticide use to be accompanied by the emergence of secondary pests such as mirids (Lu et al. 2010; Qiu 2010), as Bt cotton provides no protection against other minor pests. Hence, there is a need for such pests to be controlled by improved host plant resistance and/or seed treatments within the framework of IPM to avoid increased use of insecticides.

In addition to Bt cotton, the adoption of Bt corn has seen a steady increase over the years and is currently grown in 13 countries worldwide on more than 35 million ha (>24% of arable land worldwide) (Hellmich et al. 2008). Bt corn was first developed for resistance

Table 5. Innovative cropping systems and/or techniques that reduce the reliance on conventional pesticides

Innovative cropping practices	References
Biological:	
Biocontrol agents	Ellison et al. 2008; Furlong et al. 2008; Tanner et al. 2015
Cultural:	
Crop rotations	Vasileiadis et al. 2011,
Intercropping	Damicone et al. 2007; Baidoo et al. 2012;
Alternative tillage	Kumar et al. 2013
Companion planting	George et al. 2013
Cultivar mixtures	Raboin et al. 2012; Tooker and Frank 2012
Cover crops	Motisi et al. 2009
Mulching	Farooq et al. 2011
Biofumigation	Motisi et al. 2009
Buffer strips/Grass strips	Moreau et al. 2006,
Combination repellent and attractive species (“push-pull”)	Cook et al. 2007, Hassanali et al. 2008
Planting hedges	Morandin et al. 2011
Plant defense elicitors	Thakur and Sohal 2013
False or stale seedbed	Boyd et al. 2006
Mechanical:	
Innovative mechanical weed control	Van Der Weide et al. 2008
Robotic weed control	Slaughter et al. 2008
Applications of unmanned aerial vehicles for weed management	Peña et al. 2013

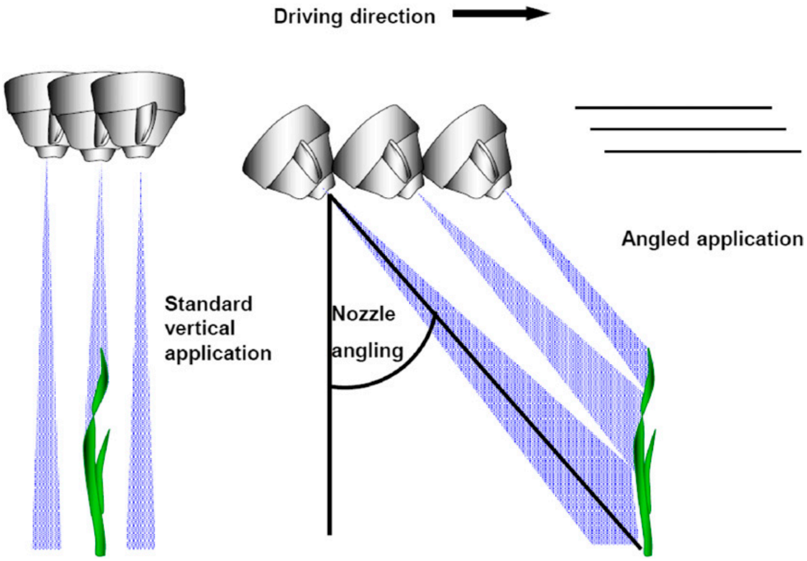

Fig. 7. Angled nozzles and standard vertical directed nozzles. Changing the spray angle from the normally used vertical spray toward an angled spray increases the potential target size of vertically oriented targets (Taken from Jensen 2012, with permission).

to European corn borer and other lepidopteran corn pests. In addition to these pests, currently available GM corn hybrids have resistance to coleopteran pests and tolerance to specific herbicides. Because of yield protection, reduced need for chemical insecticides, and improved grain quality, Bt corn hybrids represent an important IPM tool (Shelton et al. 2013).

Precision agriculture. Precision agriculture, based on innovative technologies, is a promising approach to optimize crop yields and to reduce the costs and environmental impacts of pesticide use. Precision agriculture methodologies in crop protection refer to site-specific applications of pesticides, automatic guidance of agricultural vehicles, and the identification of plant tissues affected by biotic stresses (Mahlein et al. 2012). The latter can be performed by using imaging techniques such as thermography, reflectance, and fluorescence measurements (Chaerle and Van der Straeten 2000). Site-specific application of pesticides can reduce pesticide use and decrease the economical expenses and ecological impacts in agriculture (Gebbers and Adamchuk 2010).

Improved Advisory Services and Effective Decision Support Systems

Training of and communication with farmers for a better use of the pesticides. The lack of awareness on the real risks of pesticides is one of the factors that increases exposure to pesticides. Calliera et al. (2013), through their survey study in Italy, reported a wide range of deficiencies in terms of understanding the risks related to pesticide use. In particular, 14% of the respondents did not know the necessary precautions to be taken to safeguard the environment and 65% did not leave untreated buffer zones near watercourses, although 67% understood that this was a requirement prescribed on the pesticide label. This means that there is a gap between the research, policy, and practical use of pesticides at field levels. Recently, Sherman and Gent (2014) provided general guidance for framing persuasive and effective communications to change farmer behavior. The authors highlighted that the framework of this communication is built on relationships, trust, respect for farmer experience, and tailoring recommendations to individuals and their unique needs and objectives.

An insufficient number of advisory services hinders the adoption of IPM, as reported from Poland (Matyjaszczyk 2013). From 2003 to 2011, pesticide use in Polish agriculture has almost doubled, from 0.8 to 1.4 kg/ha a.i. (Matyjaszczyk 2013). In Denmark, the independent advisory service provided a wide range of forecasting, warning, and decision-support systems and is credited with reducing pesticide use compared with use in similar cropping systems in other countries (Kudsk and Jensen 2014). A study from the United Kingdom also indicates that farmers are well trained in the country and that they consider the use of a range of cultural methods to control pests on their arable crops (Bailey et al. 2009). The support of advisors can have a direct influence on the management practices of farmers. For example, first experiences from the Project of Demonstration farms on IPM in Germany indicate that field-based scouting and face-to-face advisory support of farmers results in the reduction of TFI in winter wheat, winter barley, and winter oilseed rape (canola) by 13, 25, and 18%, respectively, compared with farms of the Reference Farm network in the same region (Marcel et al. 2015).

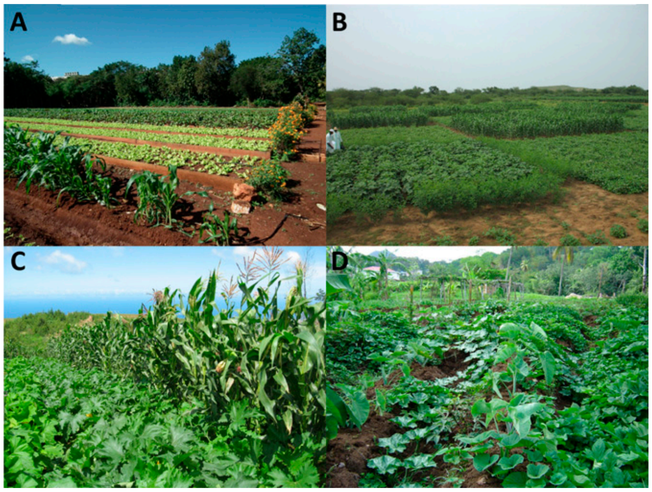

Fig. 8. Modification or redesigning of cropping systems that help reduce the reliance on conventional pesticides. Introduction of marigold (*Tagetes* spp.) and corn (*Zea mays*) as border plants for horticultural crops **(A)**, pigeon pea (*Cajanus cajan*) and sorghum (*Sorghum* spp.) as border plants of okra (*Abelmoschus esculentus*) **(B)**, Corn (*Zea mays*) used as a border plant of zucchini (*Cucurbita pepo*) **(C)**, and intercropping of a number of plant species **(D)**. These cropping systems represent major pathways for reducing the impact of pests via the introduction of plant species diversity in a given agro-ecosystem. Photos A and B are courtesy of A. Ratnadass (CIRAD, France), whereas photos C and D are courtesy of J. P. Deguine (CIRAD, France).

Decision support systems. Because the spread of pathogens and the severity of the diseases they cause vary in space and time, rational and cost-effective disease management requires the consideration of many factors. The number and complexity of these factors makes reaching a sound, rational decision for disease management a difficult task. Decision support systems (DSSs) are interactive computer-based systems that consider strategic decisions for pest control even under complex and uncertain conditions (Shtienberg 2013). DSSs help eliminate unnecessary use of pesticides by providing precise knowledge of the risk of an epidemic at field level. Therefore, farmers consider DSSs one of the most valuable IPM tools, with direct and concrete application in terms of pest control and a reduction in reliance on conventional pesticides (Rossi et al. 2012).

The effective implementation of DSSs requires efficient pest monitoring systems in order to assess the actual pest profile and pest pressure at different spatial and temporal scales. The organization and the scientific basis of existing pest monitoring systems/DSSs differ widely for the type of pest problems and countries. Pest monitoring systems/DSSs that focus on a single pest vary from those used to monitor the whole pest complex. Other factors that influence pest monitoring systems/DSSs include information on biology and damages, population dynamics, economic impact, population forecasts based on modeling, risk assessment, control methods, and pest antagonism.

Significant progress has been achieved in the last decades in the development of pest monitoring systems and DSSs. However, there are still a number of challenges that need to be overcome by fostering research. First, pest detection, characterization, and quantification—including development and validation of innovative tools for identification, sampling, and monitoring—need to

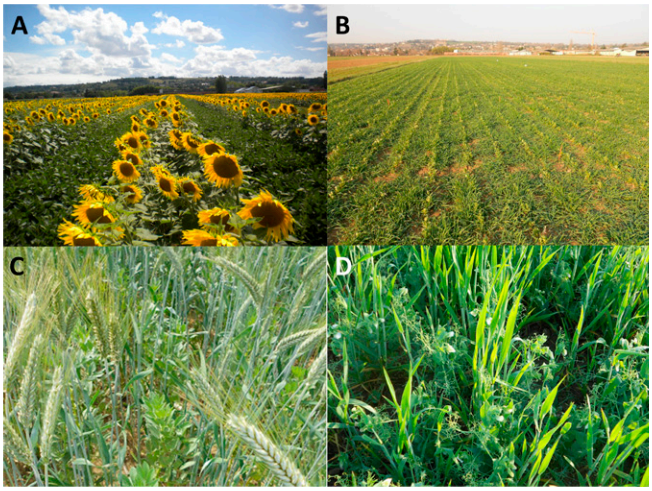

Fig. 9. Examples of intercropping systems that help reduce pest infestation level compared with monocropping systems. Soya bean-sunflower **(A)**, horse bean-triticale **(B and C)**, and durum wheat-winter pea **(D)**. Multiple cropping systems regulate pests by preventing their growth, reproduction, and spread and thus allow a reduction in pesticide use (copyright INRA France-UMR AGIR Toulouse).

be a research priority. To this end, recent advances in molecular technologies for detecting and identifying pests offer new capabilities to improve the accuracy and efficiency of existing pest monitoring systems. Second, pest forecasting—including population dynamics, improvement and validation of models based on field observations—includes research on pest biology, their life cycles, and the key factors that could restrict their populations. Several current DSSs are negatively affected due to the limited number of observation points for most pest monitoring systems and their use to predict the risk in a given area. To overcome this limit, more efforts are needed in epidemiological models and a better understanding on the biotic and abiotic covariables. This would facilitate extrapolation of the results to other situations and to predict the local level of risk. All of these factors can support tactical or strategic decision making. Third, an update of "old" threshold values is needed in the context of the actual production systems with regional and transnational perspectives. These production systems include resistance traits of the actual set of varieties, market, available control methods, and compensatory ability of crops according to actual agricultural practices. The concept of threshold levels—commonly used in current DSSs—should be extended to better understand the effect of the environment and agricultural practices while predicting damages. The relevance of such threshold levels depends on the context of their use. This is particularly true in crop protection strategies implemented at the cropping system scale. Fourth, there is a need for an effective communication with end users to develop specific tools to be used. Fifth, harmonization/standardization of DSSs is needed at regional, national, and transnational levels for all aspects of DSSs; from monitoring to forecast and communication. This will enable an efficient cross-border use of existing DSSs. Sixth, implementation and integration of pest monitoring systems and DSSs into integrated cropping systems is also needed at the transnational and regional levels. This should be done with links to other aspects of IPM such as breeding for resistance, cropping systems, and alternative control methods. Seventh, DSSs in a broader context should be the priority for research rather than single pest/crop association. This includes the consideration of farm level, production site, resistance management, global change, landscape biodiversity, etc. In addition to tactical decisions, pest monitoring systems can provide useful information on the evolution of biotic pressures over time, depending on climate change and changes in cropping practices. Eighth, socioeconomic aspects—such as end users' behavior to use or not use available decision tools—should be a part of DSSs in order to understand attitudes and obstacles of farmers while implementing such tools.

Co-innovation in codesigning potential solutions. Co-innovation is a novel and innovative paradigm. It consists of the integration of new ideas and approaches, from several internal and external sources, to a platform that aims to generate new organizational and shared values (Lee et al. 2012). Such an innovative approach proposed and adopted should contribute to create shared values for all stakeholders. More specifically to IPM, co-innovation is imperative in reaching the agricultural community and having a better impact on IPM implementation.

Approaches targeted for agricultural innovation by involving the greatest number of committed players help to codesign sustainable and tailor-made solutions that can be readily implemented. The groups of concerned stakeholders and players (e.g., growers, advisors, scientists, retailers, policy, agrochemical industry, environmental stakeholders, etc.) need to be individually identified for each co-innovation process and the related problem. Within the process, the different players bring their knowledge and discuss their stakes in the commonly identified goal and take on the role of agents who bring in knowledge, tools, and innovation. The learning process is evolutionary (Douthwaite et al. 2002). The outcomes of the interaction and evaluations of methods and tools lead to the adaptation of strategies. The core ingredients are promising technologies, motivated growers and scientists, and/or technicians or advisors who support growers to select, produce, or adopt tailor-made solutions and evaluate them. A case study on postharvest equipment in Asia shows that lower adoption rates of the new technologies were achieved in regions where the embedded scientific or technical personnel were missing (Douthwaite and Gummert 2010). A reconsideration of the traditional division of roles and responsibilities within the framework of co-innovation could allow advance practical solutions. However, the engagement with farmers and support to design systems and find solutions adapted to their needs is of paramount importance. Experience groups (Kudsk and Jensen 2014) and collective workshops (Reau et al. 2010) are useful means to identify common problems, reduce individual uncertainties, and benefit from collective experiences.

In general, the application of research results in agriculture is insufficient. Policy and legislative framework aim to improve the flow by building on a systemic understanding of innovation, i.e., encouraging and promoting co-innovation. The European Commission adopted a new approach known as "European Innovation Partnerships" in agricultural sustainability and productivity (European Commission 2015). This approach aims to enhance adaptations between the research supply and research and development demands of enterprises to support innovation, and bring together all relevant actors to increase R & D uptake in a coordinated fashion to create multifactor approaches. This framework should facilitate the formation and effectiveness of innovation-promoting organizations and multi-actor involvement, and result in need-driven, coordinated, innovation plans and the prioritization of issues in which all participants in the value chain and innovation support system can cooperatively work on an agenda for change.

An Increased Cost of Pesticides Through Taxation

The success of the pesticide reduction policy also directly depends on the relative cost of pesticides that farmers bear per unit price of their product. Farming is a business enterprise, and a reduction in pesticide use (from the point of view of most farmers) is logical only if, with similar or lower costs and workload, the economic effect of the reduced pesticide is similar to that of full chemical control. For example, a reduction of 50% TFI in winter wheat in France was expected to decrease pesticide costs by about 66 Euros per hectare (Jacquet et al. 2011), which is not economically attractive for growers in view of current wheat price of nearly 200 Euros/t (http://www.indexmundi.com/commodities/?commodity=wheat&currency=eur). Farmers will be prompted to reduce the use of pesticides if their cost of use is too high. Therefore, taxes imposed on pesticides could be one strategy to reduce pesticide use and increase farmers' awareness of the cost-effectiveness of pesticide use.

Closing Remarks

The new pesticide legislation scenario that covers all EU member states creates an opportunity to build a common IPM framework in agriculture that is based on a sustainable approach. Over the last decade, increased efforts in research and policy development have yielded useful knowledge and alternatives to conventional pesticides that can help reduce pesticide use for crops cultivated in Europe. This is especially true in light of the major challenges of efficiently increasing and protecting yields while simultaneously guarding human health and the environment. Yet, an increased investment in future human and economic resources will help the potential of nonchemical tools and their integration to prevail in applied pest management.

Several examples presented in this paper indicate the opportunities for a reduction in conventional pesticide use in many parts of Europe without significantly reducing crop yields. Adopting cropping system approaches and fostering the adoption of nonchemical tactics can achieve this. However, we still do not know which of the nonchemical tactics have the best potential under various pedo-climatic circumstances. This constitutes a long-term challenge that can be overcome by a coordinated effort of research and development.

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