Integrated Pest Management and Genetically Engineered Plants

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Summary

1. EU directives lay down, that genetically engineered (GE) organisms should neither cause direct nor indirect negative (acute or long-term) effects and pesticide use should be founded on the principles of integrated pest management (IPM). IPM is an important international political goal.
2. Results of field tests and studies on integrated farming and on the agricultural practice in GE organisms have been compiled and comprehensively analysed.
3. Integrated farming positively affects natural control agents while yield reductions are low and economic returns are stable or even increase. The analysis shows that the current agricultural practice in transgenic herbicide and insect resistant crops is largely not in accordance with IPM. Their effects on the natural regulation of pests and biodiversity are often negative.
4. The effects of genetic engineering depend on the way and concept of its application by breeders and on the agricultural practice. Indicators for the evaluation of IPM levels should be used by breeders and regulators for the assessment of new traits and varieties in order to prevent unwanted effects and to encourage more adequate pest management solutions.

Key-words: transgenic plants, integrated pest management, genetic engineering, biological control agents, biodiversity, regulation

Introduction

Most GE cultivars are herbicide or insect resistant. Transgenic herbicide resistance is often characterised as tolerance. Here the term resistance is used as defined by the Weed Science Society of America as an “inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type”. The majority of cultivars are resistant to the two non-selective herbicides glyphosate or glufosinate. These herbicides cannot be applied during the growing season in conventional crops. Insecticidal cultivars express a Bt (*Bacillus thuringiensis*) toxin, which is lethal to larvae of many butterflies or beetles. Mortality of pest larvae can be higher than 99.5% in field (Tabashnik *et al.* 2000). More than half of the total transgenic growing area is planted to herbicide resistant soybeans. Insect resistant corn, herbicide resistant canola, herbicide resistant corn, and insect resistant cotton follow referring to their growing areas.

There were still uncertainties and knowledge gaps with respect to the ecological performance of GE crops in 2000 despite the already large transgenic growing area (Wolfenbarger & Phifer 2000). It was pointed out, that key experiments were not carried out, many effects were not well documented, and the matter was sometimes simplified in a questionable way (Tabashnik *et al.* 2000). Particularly indirect effects were rarely covered in risk studies (Ammann, Jacot & Braun 2003; Schütte, Stachow & Werner 2004). Effects on weeds and insects, which are important indicators for agriculture, were often studied over too short periods, on too small plots, or outside of agricultural practice (Schütte, Stachow & Werner 2004). Comparisons of transgenic, conventional, and other agricultural practices were demanded (Wolfenbarger & Phifer 2000), which is expensive but has been done to a certain extent in the meantime. Here, the concept and measures of IPM as well as the outcome of large-scale tests are discussed. Subsequently, the agricultural practice in GE cultivars is described and assessed.

Theory and practice of IPM

THE THEORY OF IPM

Originally, IPM was defined as the combination of chemical and biological pest control agents (Stern, Smith & van den Bosch 1959; Smith & Allen 1954). Afterwards the term was broadened and used for the coordination of cultural, biological, and chemical measures (Lewis, van Lenteren & Phatak 1997; Freier, Burth & Klingauf 1999). Nature conservation measures such as the segregation and management of ecologically sensitive areas were added to an increasing list of criteria and requirements in the late nineties (Freier, Burth & Klingauf 199; EISA 2004). The primary objective is a shift from chemically based control towards biologically based management through the application of ecological knowledge, particularly on trophic links essential to the survival of biological control agents (Way & van Emden 2000; Hoppin 1996).

IPM IN PRACTICE

IPM has been tested in several farm-scale trials with durations of 4 to 15 years in Europe. Several measures were combined (Tab. 1) in all except one trial (Schütte 1990). In that trial, all decisions were left to co-operating farmers after consultations based on prognostic tools. Pesticide inputs were reduced by 10% (Schütte 1990), 30% (El Titi & Landes 1990), 68% (Gerowitt & Wildenhagen 1997) or 90% (58% without nematicides) (Wijnands & Kroonen-Backbier 1993) compared to conventional practice. Yields resembled those in conventional systems (Schütte 1990, El Titi & Landes 1990) or were about 11% lower (Gerowitt & Wildenhagen 1997, location with better soil). Net income increased by 10% (Schütte 1990) or remained stable (El Titi & Landes 1990; Gerowitt & Wildenhagen 1997: location with better soil; Wijnands & Kroonen-Backbier 1993). Site-specific management led to a higher net income at locations with highly inhomogeneous soil properties (Auerswald *et al.* 2000). Fertilizer input was also reduced by 23% to 35% (Schütte 1990; El Titi & Landes 1990; Gerowitt & Wildenhagen 1997). Yield and income losses (4%-17% respectively 13%) were found at unfavourable and steep sites without precision management mainly due to reduced fertilization (Gerowitt & Wildenhagen 1997).

Table 1. Measures of IPM

Measures
Pesticide use
1) Maintenance of non-aggressive species and small pest populations in the agricultural system through: selective products and less effective doses or partial resistance and tools*, modes or frequencies of applications in accordance with: prognostic tools, seasonal / site-specific threshold models
Land-use and land management
2) Segregation and site-specific management of unsprayed (cropped) field margins and set-aside land (e.g. headlands, flowering strips, steep and wet sites)
3) Timing of disturbance (tillage, seeding, moving)
4) Wide rotations, cover crops, summer and winter crops
5) Small blocks/mosaics of different crop species and grassland**
Management of abiotic resources
6) Adequate quantity, quality and timing of fertilizers
7) Reduction of the frequency, width and depth of tillage
8) Wide tires and light machinery

* E.g. mechanical weeding, which is not practicable between ultra narrow rows

** A mixture of animal and plant production included

The numbers and diversity of less mobile arthropod species were higher in the integrated systems (Schütte 1990; Gerowitt & Wildenhagen 1997; Auerswald et al. 2000) as well the numbers (Schütte 1990; Auerswald et al. 2000) and species (Auerswald et al. 2000) of nesting birds. Unlike in the past, small and mobile species of important predatory insects largely dominated in the nineties (Gerowitt & Wildenhagen 1997; Hassal et al. 1992). This would imply a reduction of food biomass for insect feeding vertebrates, even if total insect numbers were stable. On the contrary, large scale monitoring in Great Britain proved that numbers of most arthropod groups more or less halved every 20 years (Aebisher et al. 1991). The same rate has been found for many farmland birds (Evans 1997). The trends have not been stopped (Robinson & Sutherland 2002) and are largely due to reductions in food supply.

A negative effect of insecticides on important aphid predators such as ladybirds and hoverflies (Gerowitt & Wildenhagen 1997), and a high dependence of beneficial insects upon open-flowering plants were proved (Agricola, Scharrer & Plachter 1996; van Emden 1990). These plants provide pollen and nectar, which are necessary resources for many predatory and parasitoid insects. Results also indicated a minimum time span of 3 years for the re-appearance of many predatory arthropods after applications of broad-spectrum insecticides (Schütte 1990). Sampling of mobile arthropods has to be done at short intervals during the whole season and on large plots to trace the effects of farming practice on mobile species (van Emden 1990). Even some ground beetles characterized as less mobile (Aebischer 1991) can either crawl or fly over larger distances (Welling 1990).

A combination of several IPM measures augments its positive effects. For example, unsprayed (cropped) margins are essential for the conservation of wild arable plants, and each of these species is essential for a number of specific insect species (Heydemann 1983). Besides this trophic link, most macro-arthropods hibernate in the vegetation outside the fields and therefore depend upon uncropped margins. Wild arable plants were ranked according to their biological significance for beneficial species in summer and winter (Heitzmann, Lys & Nentwig 1992; Lagerlöf, Stark & Svensson 1992; Bürki & Hausammann 1993) and measures to conserve or re-establish arable weeds were developed (Schütte 2003).

Reduced tillage also affects weed seed banks and invertebrates. The positive effect of reduced tillage on invertebrates was mostly proved in conventional crops with cover crops. However, effects are quite small without plant cover (Krück, Ellmer & Joschko 1997; Makeschin 1997; Stippich & Krooß 1997; Wardle, Nicholson & Bonner 1999) and mixed in the case of ground beetles (Stinner & House 1990; Kromp 1999). The amount and diversity of living and dead mulch is even more important for many soil-associated arthropods than reduced soil disturbance (Krück, Ellmer & Joschko 199; Wardle, Nicholson & Bonner 1999). Herbicides affect them more negatively than disturbance by tillage (Wardle, Nicholson & Bonner 1999). Finally, adverse impacts on birds can only be significantly mitigated when farmers avoid crushing and covering nests during seeding operations. Most adult birds are biological control agents as they feed on weed seeds (in winter, Cowan 1982) and (many chicks) on insects. In warmer climates, as for example in Florida, 190 of 200 bird species are potentially beneficial (USDA/CREES 2004). IPM is the only known agricultural system, which preserves many beneficial, and non-target-species while a high level of production is maintained and income is partly increased (van Lenteren 1993). Pesticide inputs are partly substituted by labour and expertise, which is advantageous for agricultural regions. It is hence questioned, whether transgenic crops comply with IPM.

GE cultivars and IPM

HERBICIDE RESISTANT CULTIVARS

Glyphosate and glufosinate are more effective and less selective than currently used conventional herbicides (Westwood 1997) with the exception of atrazine. They have replaced integrated methods such as the use of selective herbicides and mechanical weeding (in cotton, soybeans and sugar beet), although broad-spectrum pesticides should only be used as a last resort (EPA 2004). Weed abundance was reduced in herbicide resistant soybean, sugar beet, and canola (Schütte, Stachow & Werner 2004; Buckelew, Pedigo & Mero 2000). The density, biomass, and seed rain in herbicide resistant beet and oilseed rape were reduced by a factor of three to six relative to conventional practice and the soil seed bank decreased by 20% (Heard *et al.* 2003a,b). The findings on abundance and seed bank dynamics compounded over time would result in large decreases in population densities of the field flora (Heard *et al*. 2003 b). Less field flora resulted in decreasing forage and consequently less arthropods.

In Canada, the species diversity of arable weeds declined by 26% and its density by 66% in 3-year field tests with two herbicide resistant varieties on average (Harker *et al.* 2004). These reductions were partly due to the treatments.

Beneficial natural enemies of pests, herbivores and pollinators (e.g. bees, butterflies) were reduced (Hawes *et al.* 2003). Positive effects on the flora and fauna in fields and at margins could only be found in glufosinate resistant corn.

The adoption economic threshold models and scouting is not very common. The level of adoption slightly declined in connection with herbicide resistance (Schütte, Stachow & Werner 2004). Delayed spraying had only transient positive effects in herbicide resistant beet, and only on sites with a rich soil seed bank (Dewar, Haylock & Bean 2000). The soil seed bank is reduced in the long term (Freckleton, Stephens & Sutherland 2004). Moreover, late applications can result in yield losses. They will therefore not readily be adopted by farmers. On the contrary, band spraying of conventional herbicides in combination with cutting weeds resulted in high yields and a very high natural aphid control (Häni, Ammon & Keller 1990; Schäufle 1991).

The field boundary and the structure of land use were also adversely affected by the new agricultural practice in herbicide resistant varieties. The wild plant cover at field margins was about 30% lower on average and seeding about 40% lower in herbicide resistant beet and oilseed rape. The scorching of vegetation at margins was more than doubled in both herbicide resistant crops (Roy *et al.* 2003). Soybeans were even planted in sensitive rainforest areas in Argentina. Several crop species have been replaced by soybeans in Argentina leading to less rotation and mosaic planting (Schütte, Stachow & Werner 2004). Herbicide resistant soybeans and cotton cultivars where planted in ultra narrow rows (Carpenter & Gianessi 1999; Kalaizandinakes & Suntornpithug 2001).

Finally, an USDA-adoption model indicated no encouragement of no-till practice by herbicide resistance in soybean. Reduced tillage practice increased from 25% to 48% of the US-soybean acreage before the introduction of herbicide resistance. The proportion varied between 50% and 60% afterwards (Fernandez-Cornejo & McBride 2002). Reduced and zero tillage has been increasing worldwide due to governmental enforcement. Both systems do not depend on herbicide resistance but some no-till systems largely depend on glyphosate (preemergence) sprays (van Acker, Brûlé-Babel & Friesen 2003).

INSECT RESISTANT CULTIVARS

Insect resistant cultivars are more effective than insecticide sprays, as they permanently produce a high insecticidal dose of a Bt toxin. In contrast, the Bt toxin is more selective than most insecticides. The question is thus, which insecticides or control methods are used or replaced in the new cultivars and what are the overall consequences for natural pest regulation. The changes in Bt corn and Bt cotton differ from each other.

In Bt corn, the outcome on insecticide use is unclear. There are indications for an increase lately due to secondary pests and presumably decreased numbers of predators caused by Bt cultivars (Benbrook 2003). French trials confirm this assumption as numbers of secondary pests increased. The number of parasitoids, which belong to one of the most effective guild of natural control agents, decreased by a factor of six in Bt corn. Their populations are endangered in these cultivars due to the loss of prey (Bourguet *et al.* 2002). 11 of 14 categories of beneficial insects were less numerous in Bt corn in Ohio (Jasinski, Eisley & Young 2004). The effects were low according to the authors. Nevertheless, low short-time effects often became large over time. The target pest (European Corn Borer, ECB) had formerly been controlled by beneficial insects and birds in conjunction with shredding or mowing stalks after harvest in many regions (Schaafsma, Meloche & Pitblado 1996). Only 5% of the conventional US-corn acreage had been treated against the ECB before the approval of Bt cultivars (Gianessi & Carpenter 1999). The insecticidal cultivars on the other hand have been planted on 25% to 30% of the acreage during the late nineties (Fernandez-Cornejo & McBride 2002). Bt corn is permanently planted although the target pest remained below thresholds about every third year (Gianessi & Carpenter 1999). The “over-adoption” (Fernandez-Cornejo & McBride 2002) indicates a shift from the use of treatment thresholds to prophylactic control. The decision to control a pest with insecticidal crops has to be made early when buying seeds. This hampers the use of medium-term prognostic tools. The practice with Bt corn leaves less forage for birds and endangers natural control agents. Bt cultivars were also preferentially planted by specialized corn farms and its adoption was largely correlated to the farm size (Fernandez-Cornejo & McBride 2002) encouraging an agricultural practice of planting large blocks without rotation.

In Bt cotton on the other hand, about 30% to 40% of the insecticides have been replaced, but broad-spectrum insecticides are still applied (Luttrell, Mascarenhas & Schneider 1995). Effects on the fauna were inadequately assessed as they were studied without regard for common additional sprays. The outcome on arthropods in Bt cotton was once investigated within relatively large plots over 3 years in Mississippi (Luttrell, Mascarenhas & Schneider 1995). Calculated from the decrease in insect numbers due to one insecticide application in this trial, insect numbers in conventional fields (sprayed 5 times) and Bt fields (sprayed 3 times) were equal. In Maryland, one of two specific Colorado Potato Beetle predators was significantly less abundant in Bt plots (Riddick, Dively & Barbosa 1998).

According to a review of several further studies including low dose test plants (Hoy *et al.* 1998) the outcome of Bt cultivars on biological control agents depends upon the following four aspects: Reduced applications of broad-spectrum insecticides, growing conditions (e.g. refuges) which conserve biological control agents, resistance traits without negative impacts on those species (e.g. low dose), and the provision of food sources such as pollen and nectar. Broad-spectrum insecticides are mostly sprayed (Way & van Emden 2000; Riddick, Dively & Barbosa 1998) and almost 30% of US-farmers did not plant the demanded refuges (Dove 2001). A positive outcome must be doubted. Negative impacts have been shown in Bt corn, where pests are kept far below thresholds. Populations of natural control agents are endangered in these cases.

Net income and yield results were mixed. When economic advantages were given, they were mainly due to reduced herbicide costs or high infestations (Schütte, Stachow & Werner 2004; Fernandez-Cornejo & McBride 2002; USDA/ERS *1999*). Lower yields were found in herbicide resistant soybeans (sister lines compared) and occasionally in winter oilseed rape. No significant yield changes were found in most European tests (Schütte, Stachow & Werner 2004). Positive financial impacts were found neither in the US-field nor in the whole farm-level in 1998 (Fernandez-Cornejo & McBride 2002).

Discussion

The pre-eminent demand of integrated pest management, to use economic threshold models and tolerate less aggressive species as forage for biotic agents is not fulfilled in the majority of transgenic cultivars. Non-selective control and high killing rates are not adequate for the aimed shift from treatment to bio-intensive prevention. Other important integrated plant production demands such as widening rotations, planting crops in small blocks and wide rows, conserving or creating fallow land are frequently counteracted (Schütte, Stachow & Werner 2004). The current transgenic crops provide a new way of controlling pests, which can drive agriculture further toward monoculture (Dale, Clarke & Fontes 2002). High adoption rates are mostly due to an insurance mentality, in other words, the wish to reduce production risks (Kalaizandinakes & Suntornpithug 2001).

Tab. 2. Summary of effects on the level of IPM in GE cultivars. + positive, - negative trend, / no effect, ? unclear, (-) in some regions or crops

Indicator	Bt high dose	Herbicide resistance
Selectivity	+ ?*	-
Low effect dose or partial resistance	-	-**
Use of treatment thresholds	-	-
Preservation of habitats / flora at margins	/	-
Wide row distances	/	-
Crop mosaics / moderate field size	(-)	(-)
Wide rotations	(-)	?
Disturbance through tillage	/	?***

* Selectivity outweighed through addition of broad-spectrum insecticides?

** Exception: Positive effects in glufosinate-resistant corn

*** Farmers who reduced tillage tend to plant herbicide resistant crops, the adoption of both is increasing but cause and effect are difficult to distinguish

However, low dose insecticidal cultivars and early band spraying of herbicide resistant beet (May, Champion & Dewar 2005) would comply with IPM. The computer models, which led to the decision to develop high dose cultivars, presumed too simple premises on insect behaviour and genetics (Way & van Emden 2000; Gould, Kennedy & Johnson 1991). Several studies reveal the potential of low dose strategies in combination with biological control agents and refuges (Dove 2001; Johnson & Gould 1992). These cultivars would clearly lead to long-term resistance when at least two low dose toxins were stacked. Two different insecticidal genes, which do not cause cross-resistance in the target pest, prolong the duration of resistance by a factor of 5 to 10 (Gould, Follett & Nault 1994). Low dose cultivars would also mitigate problems caused by an enhanced fitness of wild plants due to introgression (Johnson 2003; Burke & Rieseberg 2003). Moreover, resistance to selective herbicides or intensifying the production of plant volatiles, pollen, and nectar supporting biological control agents (Bottrell, Barbosa & Gould 1998) would improve the ecological performance of varieties in agriculture.
However, which nation or institution will implement these options as standard practice? Limited public funding and consultation as well as attitudes of key actors are high obstacles (Way & van Emden 2000; Auerswald *et al.* 2000). The definition of IPM was modified and discredited by industry using the term merely for pesticide and resistance management (Lewis, van Lenteren & Phatak 1997*,* Herren 2003). Low pesticide prices sometimes also undermine a potential willingness to use economic thresholds. The conservation of biological control agents is an inter-agency matter. However, regulators and scientists mostly perceive either the field of nature conservation as economically irrelevant or agro-ecosystems as "tainted" by production. This unfortunate division makes it difficult to pursue a policy in favour of both fields. Land use obligations, prognostic tools and the conservation of wild arable weeds that provide a necessary basis for organisms of higher trophic levels are insufficiently implemented. Funded headland and buffer programs for wild plants are rarely adopted (Applied Research Systems, Inc. 1999; Osterburg 2001). The importance of wild arable plants and partial resistance for biological control has widely been neglected within the recent discussion. Short-time fallow land does not conserve plant species as broad-spectrum herbicides sprayed before re-cultivation reverse any positive outcome (Raskin, Glück & Pflug 1992). It should be supplemented through co-operation between scientists, the industry, regulators, and an inter-agency action plan under the auspices of a superior international agency. Convenience should be no excuse for changes towards less biotic control agents and biodiversity.

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