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RISK ASSESSMENT

Bt Crops and Invertebrate Non-target Effects – Revisited

Steven E. Naranjo

The Controversy Continues

Who could have guessed that an unassuming soil bacterium, known for over a century to possess insecticidal properties[1], would come to rest at the center of a seemingly never-ending debate about environmental risk, food safety, and agricultural sustainability, among other issues? The ability of *Bacillus thuringiensis (Bt)*, to control select insect pests has been appreciated for over 70 years, and it occupies 90% of the bio-pesticide market. Yet only in the last 13 years have *Bt's* genes become ubiquitous in major crop plants throughout the world, via recombinant DNA technology, enabling host plant resistance to major lepidopteran and coleopteran pests and at the same time provoking continued controversy (e.g.,[2-6]). By 2007, the 11th year of commercial production, *Bt* cotton and *Bt* maize were commercially produced on a total of ≈40 million hectares in 20 countries.[7] For *Bt* cotton and *Bt* maize this represented ≈40 and 19% of the global cotton and maize production area, respectively. The assessment of environmental safety continues to be a key component of transgenic crop technology, and a recent article attempted to review our current knowledge of two issues: effects on non-target invertebrates and changes in insecticide use patterns.[8] This short piece will focus on the former, as it has clearly been the most contentious.

Meta-analysis to the Rescue – Again

In a recent article in this newsletter, Marvier[9] outlined the virtues of using meta-analyses to address environmental risk questions and provided an example of such an analysis for honey bees. Hundreds of original research papers and dozens of review and synthesis articles, discussing both laboratory and field based studies on the non-target effects of *Bt* crops on invertebrate organisms, have been published. In 2007 Marvier and colleagues[10] made publicly available a database that attempted to collate all the English-language non-target studies conducted on *Bt* crops, mainly from peer-reviewed journals but also from non peer-reviewed reports, and from industry studies conducted to support registration through US-EPA (see[11]). Four meta-analyses were subsequently published based in large part on this database[10,12-14] and have largely shown the expected lack of effect of *Bt* proteins on non-target invertebrates, regardless of whether organisms were categorized taxonomically (Order to species) or by ecological functional guilds. However, with the exception of Duan et al.[12] (laboratory honeybee studies), analyses have focused on field studies.

Marvier[9] provided a complete summary of what meta-analysis is, and that explanation will not be repeated here. Suffice it to say that meta-analysis is an efficient means of quantitatively summarizing the results of numerous similar studies in such a way that much more statistically powerful inferences can be drawn than is possible from any single study. Dozens of new non-target studies have been published since the Marvier et al.[10] meta-database was developed. Thus, in late 2008 I added an additional 39 new laboratory studies and 14 new field studies to

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the database and performed a series of meta-analyses that for the first time summarized the available laboratory studies, and I also updated the analyses of extant field studies. After filtering for non-independence in the database, the laboratory database included 134 studies on nine *Bt* crops and 22 different *Bt* Cry protein or protein combinations from 17 countries, while the field database contained 63 studies on five *Bt* crops and 13 *Bt* proteins from 13 countries. The reader is referred to Naranjo[8] for details on the analytical methodology.

Laboratory Studies

In very general terms, laboratory studies can be categorized into two different groups. One group of studies consists of organisms that are exposed directly to *Bt* plant tissues (including pollen) or pure *Bt* Cry protein. For convenience we can call these studies bi-trophic because we are dealing with only the subject organism and the *Bt* substrate. Such exposure is used for herbivores, detritivores, omnivores, pollinators, and sometimes predators and parasitoids, because many feed on plant sap, pollen, and/or nectar, or can be given Cry proteins in honey or sugar water. Another route of exposure for predators and parasitoids is exemplified in the second class of studies where the host or prey are exposed to *Bt* substrates (plant tissues or Cry proteins) and then are in turn offered to parasitoids or predators. These types of exposures are termed tri-trophic because they involve the *Bt* substrate, a host or prey organism, and the natural enemy. Tri-trophic studies introduce yet another variable that needs consideration: the susceptibility of the host or prey to *Bt* proteins and the subsequent effect of this susceptibility on the quality of host or prey offered to the natural enemy. These purported prey or host-mediated effects have been at the center of the debate surrounding some parasitoid species, but most famously for *Chrysoperla carnea* (e.g.,[15-16]). Regardless of exposure route, all studies in the database compared the effects against a non-*Bt* control, and the standardized difference between the non-*Bt* and *Bt* exposure determined the effect size used in the meta-analyses.

Looking first at bi-trophic studies, responses were variable, depending on the life history trait measured and on the guild into which the organisms were classified. Within the natural enemy group, predators showed a small but significant mean reduction in developmental rate when directly exposed to *Bt* toxins compared with non-*Bt* controls, but *Bt* proteins had no affect on survival or reproduction of either predators or parasitoids (there were insufficient data to test parasitoid development). The response of pest herbivores that are not the specific target of *Bt* crops varied. "Non-susceptible" pests (not lepidopteran or coleopteran) exposed to either lepidopteran-resistant or coleopteran-resistant crops, respectively, showed no effects from *Bt* proteins. However, the developmental rates and survivorship of "susceptible" pests (Lepidoptera or Coleoptera) were significantly reduced on average, relative to a control, when exposed to *Bt* proteins. Thus, even though a particular pest may not be considered a target of *Bt* crops from a labeling standpoint, these species as a group appear to be sufficiently susceptible to *Bt* proteins to result in lowered life history performance. How these laboratory studies relate to field efficacy is unknown. As shown by Duan et al.[11] using a larger dataset solely of honeybees, pollinators were not affected by *Bt* proteins. Detritivores were unaffected as well. A final group, consisting of charismatic butterflies (e.g., monarchs, swallowtails) and moths of economic importance (e.g., silk moths), but dominated by monarch butterflies, showed, not unexpectedly, reduced developmental rates and survival when exposed to *Bt* proteins compared with a non-*Bt* control. The monarch was of course the subject of intense investigation relative to

Bt maize which culminated in a finding of negligible risk in the field.[17]

Prey or Host Quality Matters

Tri-trophic studies are restricted to predators and parasitoids and, as noted, introduce additional variables into the equation for determining toxicity. Early on, and still to some extent today, prey or hosts (e.g., caterpillars) that are somewhat susceptible to but not lethally affected by *Bt* proteins are fed *Bt* substrates and then offered to parasitoids or predators. Oftentimes these prey or hosts have compromised growth and can generally be termed a low quality resource for natural enemies. I parsed the database so that studies using these "low quality" prey or hosts could be delineated, and then analyzed the effects on natural enemies.

Developmental rates, reproduction, and survival significantly declined in parasitoids exposed to low quality hosts feeding on *Bt* substrates (**Fig. 1**). Predators were more resilient to the effects, with only a small decrease in survival observed when given low quality prey. In contrast, some studies used prey or hosts that are not susceptible to *Bt* proteins, either by virtue of their taxonomic affiliation or, in the case of putatively susceptible insects, by using *Bt* resistant strains. When parasitoids or predators were offered these "high quality" host or prey, all of the negative effects noted with low quality resources were neutralized. The ultimate conclusion is that natural enemies are not inherently susceptible to *Bt* proteins, but they can be affected by poor host or prey quality that results from their exposure to *Bt* proteins.

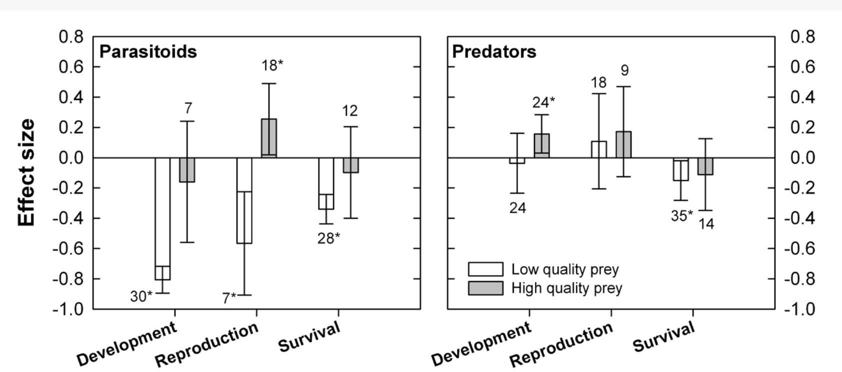

Figure 1. Meta-analyses of laboratory tri-trophic studies where prey or hosts were either partially susceptible to Cry proteins, and thus displayed reduced vigor (low quality), or were non-susceptible or resistant to Bt proteins (high quality). Numbers indicate total observations for each biological parameter and error bars denote 95% confidence intervals; error bars that do not include zero indicate significant effect sizes (*, $P < 0.05$). Negative effect sizes are associated with compromised performance on Bt compared with non-Bt controls. (Reproduced from Naranjo8 with permission from CABI.)

Field Studies Reprised – Control Method Matters

Field studies permitted the testing of three different and independent hypotheses: 1) *Bt* vs. non-*Bt* plots, neither of which received any insecticide treatments; 2) unsprayed *Bt* crops vs. non-*Bt* crops receiving insecticide treatments to control the pest targeted by the *Bt* crop; and 3) *Bt* vs. non-*Bt* crop in which both were treated with insecticides to control target and/or non-target pests. The addition of 14 new studies did not qualitatively alter the patterns for ecological functional guilds observed by Wolfenbarger et al.[14] regardless of the hypothesis tested, but did allow the examination of *Bt* eggplant and *Bt* rice in addition to cotton, maize, and potato from that original study. Analyses of these two new crops indicated that no arthropod functional guilds were affected by *Bt* under hypothesis 1 (insufficient data were available to test 2 and 3 for these crops). As before, parasitoid abundance in *Bt* maize was significantly reduced, which can be explained simply by the fact that most of the parasitoid studies were comprised of a single specialist parasitoid of the European corn borer, the main target of *Bt* maize. Predators were also slightly reduced in *Bt* cotton, and this too was likely the result of target caterpillar prey reduction. Non-target pest abundance, however, was largely unaffected by *Bt* crops, which would suggest in part that changes in natural enemy abundance are not negatively influencing control of other pests in these systems.

Spraying insecticides on both *Bt* and non-*Bt* cotton also resulted in neutral effects on various functional groups, but applications of insecticides on the non-*Bt* crop (cotton, maize, and potato) compared with an unsprayed *Bt* crop (hypothesis 2) revealed dramatic increases in the abundance of nearly all non-target functional groups in the *Bt* crop, including natural enemies. This scenario largely represents a comparison of alternative methods for suppressing the target pests, and the ultimate conclusion is that insecticides have a much more dramatic negative effect on non-target organisms than do *Bt* crops.

Conclusions

The debate continues on the issue of non-target effects of *Bt* crops, but meta-analysis has the potential to focus the debate by providing a robust and quantitative framework for combining results from multiple independent studies while minimizing the positive or negative impact of any single study that may be poorly replicated or conducted. It provides for a collective wisdom to guide risk assessment and regulation. As exemplified here, meta-analysis also enlightens our perspective of the important components to consider such as, for example, prey or host quality in tri-trophic studies on natural enemies, and realistic comparison of alternative methods of controlling insect pests.

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Cultivation of GE Oilseed Rape with Different Herbicide Resistances

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Oilseed rape (*Brassica napus* L.) engenders special concern regarding gene flow, due to its potential for outcrossing, for volunteer emergence, and to form temporary feral populations. If different genetically engineered (GE) herbicide-resistant oilseed rape cultivars are grown in neighboring fields, seeds and subsequent volunteers with multiple herbicide resistances (HR) can arise.[1] If multiple resistant volunteer plants are not removed, e.g., by using an appropriate herbicide, they can serve as a source or sink for further cross-pollination.[2] In addition to potential problems with multiple resistant volunteers following crop rotations, the combination (´stacking`) of different GE traits in one plant may affect HR gene expression and thereby the reliability of expression-based transgene detection. In a recent paper,[3] we presented the results of a biennial large-scale field experiment with two different GE oilseed rape lines cultivated on adjacent plots to investigate the frequencies of HR gene dispersal, the expression of HR genes in double-resistant plants, and the sensitivity of plants to conventional herbicides.

Adventitious Transgenes in Seed Harvest

Field experiments with GE winter oilseed rape consisted of two double plots of 1 ha each in which glufosinate-ammonium resistant (LibertyLink; LL) plants and glyphosate resistant (Roundup Ready®; RR) plants were grown side by side, separated either by 0.5 m or by 10 m isolation distance. Seeds were sampled along 2 m wide sampling strips located at 0, 10, 20, 40, and 70 m within each plot. Samples were analyzed by phenotypic herbicide germination tests and by specific polymerase chain reactions (PCR). The design of the field experiments not only allowed determination of mutual outcrossing rates in the adjacent oilseed rape plots, but also quantification of the extent of transgenic seed dispersal by harvesting machines.

As expected there was a general tendency for lower outcrossing rates if the gap width was increased to 10 m. Within plots the frequency of double-resistant seeds decreased sharply with distance from the pollen source. Although distinct differences were observed between years and between the different transgenic HR lines, outcrossing frequencies were always clearly below 0.5% at 40 m within the recipient field.

Outcrossing is not the only mechanism for gene flow between plots. To determine the contribution of seeds dispersed by harvesting machines (seed-mediated gene flow) to the adventitious presence of HR genes originating from the adjacent plot, seed samples were subjected to additional PCR analysis. 16% of the seeds from the first sampling point (size: 2 m x 5 m) in the RR plot contained the LL-specific HR gene. After cleaning the combine of seeds from the previously harvested LL plot, only 3.2% of the RR plot seeds contained the LL-specific HR gene. Although at subsequent sampling points the percentage of dispersed seeds was much lower and approached zero at the end of the second sampling strip, these residual seeds can have a great impact on the adventitious presence of transgenic seeds in the harvest. Therefore, to reduce gene flow between different GE oilseed rape fields or to non-transgenic rape fields, it is recommended to not use the same machinery for sowing and harvest of the different cultivars.

Double Herbicide Resistant Volunteers

In addition to the adventitious presence of transgenic seeds in the harvest, another consequence of outcrossing from GE herbicide-resistant oilseed rape can be the emergence of volunteer oilseed rape with new HR traits. Seeds from oilseed rape pods shattered prior to and during harvest can germinate immediately, unless secondary dormancy is induced by environmental stress conditions like water shortage or darkness.[4]

One goal of our field experiment was to compare the number of double-resistant seedlings emerging on stubble from pollen-mediated gene flow between the two HR plots. Outcrossing frequencies were obtained by seed analysis. Volunteers emerging after harvest were selected by a dual application of the respective other herbicide. The average number of double-resistant volunteers was between 1.5 and 6 plants per m^2 at the border of the plots facing the adjacent plot, while it was typically around 0.5 plants per m^2 at distances of 40 m and higher. Although double-resistant volunteers declined within the plots as expected for pollen-mediated gene flow, there was not a good correlation between these data and the outcrossing frequencies determined by seed analysis. Similar observations were made by Beckie et al.[2], who investigated gene flow between commercial fields of glyphosate resistant and glufosinate-ammonium resistant oilseed rape. The emergence and/or survival of oilseed rape volunteers are likely to be affected by a number of biotic and abiotic factors (e.g., humidity, soil structure, occurrence of predators), which can vary within a field and among different field sites. Variability of these factors within the field site as well as insufficient selection by the herbicide applications may account for heterogeneities in the occurrence of double-resistant volunteers per m^2.

Variation in Gene Expression

Herbicide resistance genes in GE oilseed rape lines are regulated by different plant virus promoters, which have several short stretches of DNA sequence identity and might therefore be prone to homology-dependent gene silencing. Double-resistant plants and hemizygous backcross plants were obtained by reciprocal crosses of the LL line Liberator C/6Ac and the RR line Lirajet GT73. Expression of the HR genes *pat* and *cp4 epsps* was determined in double-resistant plants containing one copy of each gene, as well as in the parental homozygous LL and RR oilseed rape lines and in backcrosses with the respective non-transgenic oilseed rape cultivars.

Under controlled greenhouse conditions at 22° C, the expression level of both genes was dependent on the developmental stage; older plants at the 8- to 10-leaf stage had about a 2-fold increase in expression (**Fig. 1**). Although the expression level of *pat* and *cp4 epsps* genes in single-resistant as well as in double-resistant plants varied with the developmental stage of the plants and with temperature, the presence of an additional transgene in the LL x RR hybrids never resulted in transgene inactivation. Instead, a gene dosage effect was observed. Relative amounts of the HR proteins were about 50% higher in parental homozygous plants as compared to hemizygous offspring plants. This agrees with some reports on the effects of gene copy number and zygosity on transgene expression in different plant species and is thought to reflect transformation events with stable transgene expression.[5] In contrast, there have also been many reports from monocot as well as from dicotyledonous species where no positive correlation between transgene dosage and expression was observed.

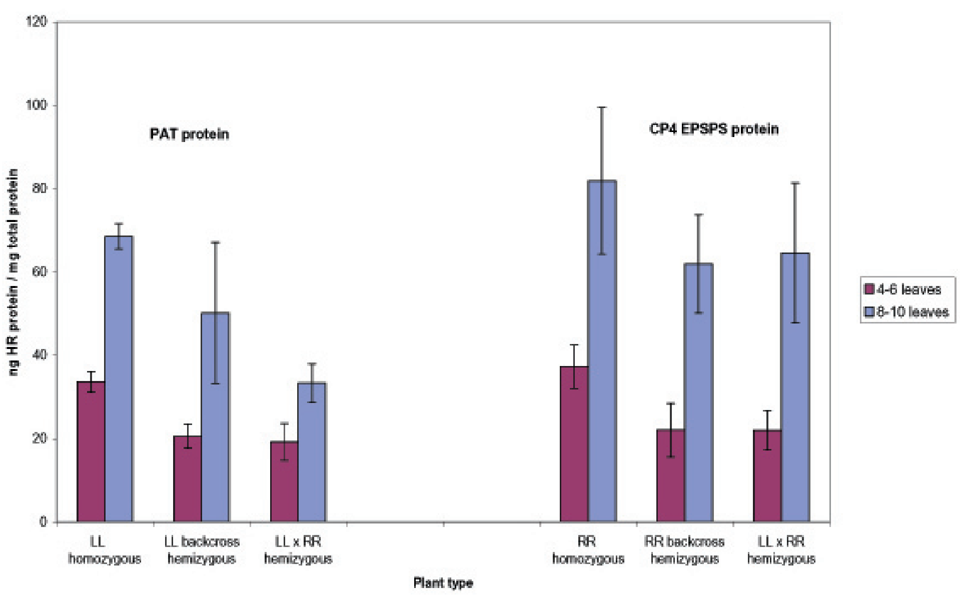

Figure 1. Mean values of HR gene expression in GE homozygous and hemizygous oilseed rape during plant development, shown as relative amounts of the HR proteins PAT and CP4 EPSPS (+/- SD).

Herbicide Sensitivity

In order to avoid weed problems with volunteers carrying multiple herbicide resistance, it is essential that double-resistant oilseed rape plants can be killed by herbicides commonly used to control oilseed rape volunteers in the crop rotation. Therefore the sensitivity of the single- and double-resistant GE oilseed rape plants to three selective cereal crop herbicides commonly used for control of broad-leaved weeds was investigated under greenhouse conditions. At the recommended dosage, each of the herbicides had a very good efficiency against all tested oilseed rape cultivars, lines, and crosses. Although efficiencies varied at reduced dosages, variations could not be attributed to the transgenic HR traits. Oilseed rape plants with multiple herbicide-resistance traits can be successfully controlled by herbicides commonly used for volunteer control, as reported previously.[6]

In view of the increasing number of weeds developing resistance to glyphosate herbicides, successful weed management practices in GE glyphosate-resistant oilseed rape requires the use of additional herbicides. It is therefore important that single- and double-resistant plants are compatible with herbicides commonly used in oilseed rape fields. For three selective herbicides, which were applied at five different dosage rates, no differences in sensitivity between the non-transgenic cultivars and the GE lines and crosses were observed. Moreover, resistance to the complementary herbicides glyphosate and glufosinate-ammonium was not affected by the second HR gene. Therefore conventional selective herbicides can be used in addition to the complementary non-selective herbicides to control weeds in the transgenic HR oilseed rape crops.

In conclusion, in the case of the GE lines investigated here, neither transgene integration nor the combination of the different HR genes resulted in any pleiotropic effects affecting the sensitivity to other herbicides.

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Can GE Crops Benefit Developing Countries? Research methods, findings, and recommendations

Genetically engineered (GE) crops have been a topic of hot debate in recent years, resulting in a plethora of opinions and studies, particularly with regard to their potential impact in the developing world. While the debate can be very polarized at times, a recent report by the International Food Policy Research Institute (IFPRI) finds that, overall, the economic effects on smallholder farmers in developing countries are positive. This conclusion is based on a comprehensive review of the methods and findings of peer-reviewed, applied economics studies of the impact of GE crops on developing economies, of which there are very few, relative to the vast amount of literature on the topic.

The IFPRI report finds that while there are numerous reviews of findings, there are very few on methods. Noting the importance of the latter, which influence the nature of economists' findings and how they are interpreted, the report identifies specific gaps in methodology and calls for methodological advancements to improve future research. The review considers the implications of GE crops not only for farmers, but also for consumers, the agricultural sector as a whole, and international trade. The report also suggests directions for further inquiry, with the ultimate goal of providing policymakers and farmers with more solid information on which to base their decisions.

Impact on Smallholder Farmers

In the first decade of GE crop adoption, IFPRI identified 137 international peer-reviewed studies examining the economic impact of these crops in developing countries from 1996 – 2007. Most of the studies were of farmers and based on data that were collected predominantly *ex post* (after the fact). Taken together, these studies show that adoption of GE crops is economically beneficial for farmers, who experience—particularly in the case of Bt, or insect-resistant, cotton—reductions in pest damage and insecticide use, as well as increases in yields, although the latter is highly variable, according to the findings of different studies.

These results point to estimation bias among the studies reviewed. The two main types of studies—partial budget and specific statistical models—do not address the diversity of growing conditions, farm sizes, and crops being cultivated that might influence farmers' decisions and success rates. Results depend heavily on the geography and season in which studies are conducted, including conditions that may vary, such as weather, severity of pest infestations, and input prices. They also depend on the social and economic circumstances of a given farming community. Because the partial budget model only allows for one farming activity to be studied at a time, it is difficult to accurately assess the net economic impact of adoption. Moreover, averages disguise the fact that GE crops may not be universally profitable, even if they are advantageous to certain farmers.

> "...many of the studies reviewed also suffer from selection bias, which can result from the self-selection of farmers,..."

In addition to estimation bias, many of the studies reviewed also suffer from selection bias, which can result from the self-selection of farmers who choose to adopt GE crops, or selection of farmers through a company extension program. In addition, small sample sizes and reliance on farmer recall for data can lead to measurement bias. Daily monitoring practices that could result in more precise, objective measurements are time-consuming and expensive, and thus have been used infrequently in past research.

In the future, studies on the impacts for farmers should also expand their scope and examine details in greater depth. Current research is limited by the relatively low number of scientists pursuing these questions. Most studies consider the so-called "first-round" impact of GE crop adoption. Few have gone further to consider the long-term implications for human health, poverty, inequality, and the environment, especially for communities. Finally, because adoption has been largely limited to a few crops (mainly cotton, maize, and soybeans) and to only two technologies (insect resistant and herbicide tolerant), a broader investigation of other crops has not yet been carried out.

Consumer Awareness, Preferences, and Behavior

Understanding consumer attitudes and willingness to pay (WTP) with respect to GE foods is extremely important because consumer demand can determine a farmer's propensity to adopt GE crops. According to the literature, consumer attitudes can vary drastically depending on the level of available information, education levels, and geographic location (i.e., rural vs. urban), indicating that preferences are likely to change over time.

The IFPRI review of consumer studies shows two major trends. First, the WTP for non-GE foods tends to be higher in developed countries, and differences in consumption patterns are largely the result of risk aversion. Second, information dissemination has the greatest likelihood of influencing consumer preferences, especially when the information is negative. In the future, studies should link farm and consumer research conducted in the same developing economy. Currently, most consumer studies focus on products that have yet to be commercialized and planted.

There is also a need for broader geographic range in research on consumer preferences and willingness to pay. Of the 28 articles written on the subject, 13 are on Chinese attitudes, which may not be relevant in other countries or regions. Only three studies have been conducted in Latin America and none in Africa. Preferences in developing countries may be different from those in North America and Europe since market chains are shorter in the former and consumers could know the producers, potentially affecting their willingness to buy GE crops. Prices may also be a more decisive factor in developing countries, although research elsewhere suggests that a small percentage of consumers will avoid GE foods at any premium.

Finally, the methods used thus far to assess consumer WTP for GE food have not been especially advanced and could benefit from recent methodological improvements in the consumer choice literature. An approach that combines revealed and stated preferences would be more effective, but cannot be undertaken until GE food products are more widely available. Since these crops can be politically sensitive—and, in many cases, poorly understood—the wording of questions and the researcher's choice of methods have a disproportionate effect on findings. Also, as consumer attitudes change with the level of information available, research must be constantly updated to account for shifting preferences.

Agricultural Sector Studies

Sector studies are also largely *ex ante*, but comprise some of the most nuanced research to date on the economics of GE crops. Economic Surplus models have been used to predict whether adoption will benefit developing country economies overall. These models take into account the magnitude of a country's production, its rate of GE crop adoption, whether it has an open or closed economy, and whether it is a price maker or taker, as in the case of small countries, which cannot affect world commodity prices and are forced to "accept" them. In certain cases, stochastic models have been used to account for risk.

"The most common method used in sector studies is an ex ante Economic Surplus approach, which does not address factors affecting farmers' decisionmaking,..."

The most common method used in sector studies is an *ex ante* Economic Surplus approach, which does not address factors affecting farmers' decisionmaking, such as transaction costs or income effects due to changing prices. Research is usually limited to a single market, ignoring possible influences from input markets and markets for substitute crops or complementary goods. Models also frequently portray partial equilibria, assume homogenous growing conditions and well-functioning markets (for simplification purposes), and have yet to incorporate negative externalities, such as effects on the environment and human health. Future studies should address these shortcomings.

Distributing Benefits and the Role of Institutions

Adoption patterns have considerable influence on who benefits from the introduction of GE crops. Research in developed countries shows that strong intellectual property rights (IPRs) may help attract innovators, but they can also lead to increased seed prices. Strong public-private partnerships, investment in biotech breeding capacity, regional licensing, and research networks may help balance these tradeoffs and still support innovation. The dissemination of information and other institutions, including laws and regulations, play a critical role in determining who benefits and loses from GE crops.

Countries can also invest in extension systems, farmer knowledge, and strong market channels to help farmers make educated decisions regarding GE crops. These initiatives should be informed by research to achieve optimal crop choices, adoption patterns, and market reforms for a given country. Further information on the health, social, and environmental impacts of GE crops is essential for developing a more complete understanding of the biotech sector's benefits. This investigation becomes more feasible as better data become available and as adoption continues, and should therefore be pursued in the next generation of research.

"Time series data that account for year-to-year variability, damage abatement, and stochastic models have been significant improvements in recent research,..."

Trade Studies and International Markets

To determine the impact of GE crops on the international market, researchers have applied three different methods to assess consequences for both adopting and non-adopting countries, as well as the effects of market segregation and trade regulation. Studies of bilateral trade flows help to determine the effects of association with GE crops and market access; partial equilibrium models analyze vertical and horizontal linkages between different sectors in different countries; and general equilibrium models, which are highly aggregated, analyze world markets.

International trade studies in particular agree on three main conclusions. First, countries gain advantage by adopting GE crops early, while countries adopting later benefit less. Second, potential export declines due to biotech regulations have been overstated and are unlikely to outweigh the gains from adopting and using GE crops. Third, as increasing yields lower prices (as indicated by trade and surplus models), consumers benefit and producers lose. Research, however, has not yet considered the case of smallholder farmers who consume their own crops and are often net purchasers of food. Such research would be most relevant for farmer and national-level analysis.

While studies of the implications of GE crops in international trade have provided an adequate general assessment of the situation, several shortcomings are apparent, in part because the models are highly dependent upon the accuracy of underlying data and assumptions. One important flaw is the tendency to aggregate sectors and regions, a problem which often results when researchers use the Global Trade Analysis Project (GTAP) database. Not all markets for GE crops operate in perfect competition, and the partial equilibrium model can't account for certain circumstances, such as an exporter selling to a restrictive market. Lastly, most studies are based on assumptions of market behavior, and there is consequently an absence of *ex post* data on GE crops in international markets.

The Way Forward

In summary, the IFPRI report finds that impact studies on farmers need to consider estimation, selection, and measurement biases. Time series data that account for year-to-year variability, damage abatement, and stochastic models have constituted significant improvements in recent research, but further methodological advances are necessary. Consumer studies should consider employing combined stated- and revealed-preference models. Sector and international trade studies will improve as background data become more reliable and readily available, and as models account for specific in-country differences.

Finally, extension systems and institutions are essential for ensuring that relevant information and findings reach farmers and policymakers. Adoption patterns need to be carefully watched to ensure maximum economic benefits, as well as poverty reduction and positive contributions to human health and the environment.

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*The full report, "*Measuring the Economic Impacts of Transgenic Crops in Developing Agriculture during the First Decade: Approaches, Findings, and Future Directions*," can be found at http://www.ifpri.org/sites/default/files/publications/pv10.pdf.

IFPRI has also compiled an online bibliography of relevant studies, available at: http://www.ifpri.org/publication/becon.

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