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The Myth of Natural Barriers
Is Transgene Introgression by Genetically Modified Crops an Environmental Risk?

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Keywords. Introgression; genetic modified organism (GMO); risk assessment; science and technology.

Abstract. *Genetically modified (GM) crops under open field conditions are a complex and controversial issue. Ecologists are discussing about the possibility that a transgene belonging to GM plants could spread to native populations through a process known as introgression – the stable incorporation of a gene in the host genome able to generate a differentiated popula-*

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Rivista di Biologia / Biology Forum 101 (2008), pp. 195-214.

tion. The ecological consequences of a transgene introgression in plants or bacteria are not yet well understood, but could be significant. In this critical review we consider vertical and horizontal introgression. We analyse the biochemical and genetic constraints, and environmental factors that limit the possibility of transgene spread; meanwhile we show cases in which the natural barriers are overcome. Then we discuss the overall management of GM crops, noting the shortcomings and approximations of risk assessment based on linear thinking typical of the biomolecular approach. Finally we suggest to explicitly weight facts together with values and we encourage the undertaking of an ecological perspective, encompassing the complexity of (non-linear) relations between organisms and the environment.

1. INTRODUCTION

Research, development and large scale farming of genetically modified (GM) crops is rapidly varying the worldwide agriculture scenario. In 2007, the global area of GM crops reached 114.3 million hectares, corresponding to a market value of 6.9 billion dollars which represents 20% of the global seed market (www.isaaa.org [2007]). Indeed, the so-called “gene revolution” does not seem to be free from consequences and both public opinion and scientists have been showing increasing concern for the toxicological, ecological and more generally for the economic and social fallouts of this enterprise.

In this study, we will consider scientific literature relative to a specific kind of ecological risk, connected to open field trials involving GM crops, that is, the uncontrolled and undesired spread of DNA segments belonging to GM crops through genetic flow. The specific risk is connected to a genetic flow followed by *introgression,* which involves the stable incorporation of genes, coming from GM crops, into wild relatives, with unpredictable consequences for yields, biodiversity and ecosystem equilibrium. Some transgenes that provide, for example, insects or extreme temperatures or even drought resistance may confer a trait which could enable a species to gain an unfair advantage over the others, compromising the biodiversity that stabilizes ecosystems. Moreover, if the new species were weeds they would be harder to control and therefore the yields would be lower.

It is commonly agreed among the experts that there are *natural barriers* that make introgression of transgenes, from GM crops to organisms living in the same ecosystem, highly unlikely yet not impossible. In order to evaluate the actual adequacy of natural barriers to gene flow, the most up-to-date knowledge concerning the mechanisms of gene introgression has to be clarified. Moreover, the ascertained cases of transgene introgression are to be analysed.

Nonetheless, as we will see, the complexity of gene flow models in ecosystems and the level of ignorance as to their dynamics is such that it is hard to answer unambiguously to the following question: Is transgene introgression by genetically modified crops an environmental risk? Indeed the complexity is caused, on the one hand, by the necessity to deal with a large quantity of uncertain and correlated data along with a great amount of ignorance and, on the other hand, by the need to tackle the problem by using different disciplines, and therefore different perspectives, methodologies and aims. Thus, transgene introgression is an excellent case study for identifying some fundamental conceptual tools to approach complex issues characterized by risk, uncertainty and ignorance.

The purpose of this review is to provide a comprehensive image of the most recent scientific insights involving introgression. Furthermore, in the light of this overall updated scenario, it aims to discuss the controversial issue of the environmental consequences of this phenomenon.

2. THE NATURAL BARRIERS TO VERTICAL GENE INTROGRESSION

Vertical gene transfer (VGT) takes place via sexual crossing. In the flowering time, pollen fertilizes the oocyte of the same species. *Hybridization* is the term used when pollen of a plant belonging to a given differentiated population fertilizes a plant of another population. Pollen dispersion is considered as the main cause of gene flow from one differentiated population to another and it is quite a common natural phenomenon. However, the process of introgression occurs in many steps which involve several hybrid generations. This phenomenon may be facilitated by the coexistence of different generations in many plant species for many years. In the case of GM crops, transgenes can be preserved in the crop area even for a long time owing to "volunteer" populations of plants that grow spontaneously years after harvest. The *volunteer* population works as a *seed bank* that can provide the transgene to the hybrid generations which may exist for a long period of time.

Many studies have been concentrating on the "hybrid zones", using specific isoenzyme activities and gene sequences as molecular markers that allow us to hypothesize a plausible history of gene exchange. Overall, 165 cases of introgression between plants have been determined but there are many different reasons for believing that this estimate is well below the actual entity of the phenomenon (Stewart *et al.* [2003]). It is worthwhile noticing that two-thirds of the documented cases involve plants belonging to the same species and only one-third concerns different species. The introgression of a gene seems indeed possible only if the two differentiated populations have the same *gene order* (chromosome arrangement) and it is facilitated by the gene proximity to other genes that confer a fitness advantage in the chromosome.

A few natural barriers inhibit the chance of gene introgression between any given GM plant and a relative population. In order to overcome these barriers the two species must: (1) be sexually compatible, (2) grow near one another, and (3) have partially overlapping flowering times. Moreover, (4) the first generation F_1 hybrids must persist for at least one generation and be sufficiently fertile to produce backcross hybrids (BC_1). Finally (5) the transgene must have a selective advantage for the wild relative and (6) backcross generations must progress to the point at which the transgene is incorporated into the genome of the wild relative. Bearing these general premises in mind, Neal Stewart and his colleagues propose a classification of different GM crops with the expectation of introgression and they distinguish firstly, between very low risk crops (e.g. soybean, potato, peanut, common bean), secondly, low risk crops (e.g. corn, rice, cotton); moderate risk crops (e.g. wheat, sugar beet, sunflower, canola) and finally, high risk crops (e.g. sorghum) (Stewart *et al.* [2003]).

Stewart and colleagues believe that natural barriers can be strengthened by using appropriate strategies, such as transgene insertion either into the appropriate gene locus or into the chloroplasts, or even by fertility reduction of the GM species. However, they agree on the fact that at present, appropriate evaluation of a transgene introgression risk cannot be made. This is not only due to the unavailability of adequate systems to identify the cases of introgression but more generally because genetic knowledge and introgression ecology is still too limited to make an adequate risk assessment (Stewart *et al.* [2003]).

3. DOCUMENTED CASES OF VERTICAL TRANSGENE INTROGRESSION

A systematic research on transgene vertical introgression is currently unavailable, therefore, the documented cases concerning GM canola, sunflower, creeping bentgrass and potato are likely to be underestimated.

Canola

Gene flow between canola (*Brassica napus*) and wild turnip (*Brassica rapa*) has been known for a while now and it is well documented (Hansen *et al.* [2001]). Nevertheless, the first evidence of transgene introgression coming from commercial GM canola crops is relatively recent (Warwick [2003]). A research on this subject has confirmed that introgression can occur spontaneously and that hybrids have a high potential for producing transgenic seeds (Halfhill *et al.* [2004]). Other research has experimentally demonstrated that the transgene can confer a selective advantage to the hybrids and that this can contribute to stabilizing the introgression (Stewart *et al.* [1997]). In particular, the Bt transgene (*Bacillus thuringiensis*) has been observed to increase *B. Rapa* fitness in the presence of insect high density (Vacher *et al.* [2004]; Zhu *et al.* [2004]).

A research study conducted by the Department of Agriculture and Agri-Food of the Canadian Government in 2005 shows that the transgene which confers herbicide resistance to canola (Canadian oil low acid) slowly spreads to the wild relative populations, specifically the *B. Rapa*, giving rise to new plants with single or multiple resistance inserts. Hybrids can cross both with transgenic crops and volunteer plants, grown from the seed bank. In this way, the transgene persistence in the area is guaranteed (Legere [2005]).

The wild species that gain herbicide resistance interfere with crops and determine a yield reduction. The farming systems (for example rotations) have to be modified and the weed control strategies could become more complex and expensive. Moreover, transgenic plants can crossbreed and therefore develop multiple resistance to herbicides to the point of compromising their presence on the market, as revealed only four years after their introduction in Canadian fields (Hall *et al.* [2000]). Finally, the gene flow can reach nearby crops and create economic and social problems, above all, when hybridization involves crops that are meant to be commercialized as organic or GMO free (Legere [2005]). However, it is plausible to believe that herbicide resistance confers a fitness advantage only when the herbicide is applied. This kind of introgression should not produce any ecological problems that are involved in the parasite resistance transgenes, such as *Bacillus thuringiensis* genes.

Sunflower

A study conducted in the US and published in 2002 has documented that transgenic sunflower can hybridize with common sunflower *Helianthus annuus*, as the two crops share their flowering time (Burke *et al.* [2002]). It has also then been observed that when the wild sunflower hybridizes with the transgenic Bt it can produce a higher number of seeds compared to the wild type thus providing the first evidence that a wild GM population can prosper and spread in the environment (Snow *et al.* [2003]).

Creeping bentgrass

The transgenic variation of creeping bentgrass (*Agrostis stolonifera*) can hybridize with even distant wild populations. A research published in 2004 documented the presence of *Agrostis stolonifera* wild samples that incorporate an active transgene (CP4 EPSPS that confer a resistance to the glisofate herbicide) in their genome. The gene flow was found within two kilometers from the borderline with the transgenic crops, but wild samples containing the transgene were detected even twenty kilometers away (Watrud *et al.* [2004]).

Potato

Although the potato (*Solanum tuberosum*) is considered a very low risk crop in the Stewart classification, a study published in 2004 on the environmental safety of a transgenic nematode resistant variety of potato documented gene flow towards wild relatives that grow in the proximity (Celis *et al.* [2004]). The problem is deepened by the fact that the transgenic variety is grown in one of the most important areas of biodiversity conservation (The Central Andes), where 130 wild species of potatoes that are sexually compatible with transgenic crops had been documented. Nonetheless, the scientists who conducted this research continue to follow the Nuffield Council of Bioethics position whereby the risk of compromising biodiversity by introgression is not a sufficient reason for banning the use of GM crops in developing countries, where a response to denutrition (Nuffield Council on Bioethics [2004]) would seem to be an urgent issue.

4. THE NATURAL BARRIERS TO HORIZONTAL GENE INTROGRESSION

Horizontal (or lateral) gene transfer (HGT), is a non-parental-to-offspring, non-sexual transfer of genes. The mechanism of HGT from microorganisms to plants is well known due to the studies on *Agrobacterium tumefaciens*, used as a privileged exogenous DNA vector in the research and industrial development of GM organisms. The mechanism by which a bacterium can incorporate exogenous DNA takes place in three different ways: (1) transfer of gene sequences from one bacterium to another via a bacteriophage virus (*transduction*); (2) plasmid exchange (*conjugation*); (3) incorporation of molecules of "naked" DNA present in the environment (*transformation*).

The most probable way for a potential HGT from a plant (which may or not be transgenic) to a bacterial cell is transformation. Nevertheless, a sequence of natural barriers has to be overcome (Bertolla and Simonet [1999]; Nielsen *et al.* [1998]). The first barrier: *the genomic DNA must leave the plant cells.* This can happen in the soil after plant death. The consequent cell lysis releases 'naked' gene material. The second barrier: *the released DNA in the soil must be preserved and not degenerate.* Most of the released DNA immediately undergoes physical and enzymatic degradation, caused by the DNAses activated by the cell lysing. However, a fraction of the DNA is adsorbed by the grains of clay and sand therefore avoiding the destructive enzymatic action. It has been observed that 1g of montmorillonite can adsorb up to 30mg of DNA, the equivalent of 10^{30} genomes of *Escherichia coli* (Ogram *et al.* [1987]). In this way, whole portions of genome are most likely to be preserved in the soil for weeks or months after plant death. This adsorbed DNA is available to transform bacteria. The third barrier: *Bacteria have to express competence under natural growth conditions*. Although average soil can provide optimal conditions for bacterial transformation, only few terrestrial bacteria showing state of competence have been detected (Nielsen *et al.* [1997]). The fourth barrier: *the DNA molecules have to adhere to the surface of competent bacterium*. Some bacteria recognize and bind only DNA that contains specific recognition sequences (8-10bp). Other natural competent bacteria did not exhibit such specific adhesion mechanisms and, on the other hand, any DNA is bound efficiently to sites consisting in membrane proteins stabilized by competence signalling proteins. The fifth barrier: *Exogenous DNA have to escape the restriction-modification systems protecting the host DNA.* Bacteria have protection enzymatic systems that identify and degrade exogenous DNA. However, most competent bacteria are believed to generate single-stranded DNA during translocation of the DNA into the cytoplasm, which may not be affected by restriction enzymes. Moreover, the presence of saturating amounts of DNA, or a leaky restriction barrier, can lead to successful transformation of cells that captured DNA. The sixth barrier: *Exogenous DNA must be stabilized in the bacterial genome.* The maintenance of exogenus DNA requires integration into the bacteria chromosome or its autonomous replication based on the presence of replication functions and an origin of vegetative replication (oriV) in the DNA. The seventh barrier: *The gene integrated into the bacterial genome must be expressed correctly.* More specifically, once the gene is stabilized in the bacterial genome, the mechanisms of gene expression must correctly synthesize the corresponding peptide or protein. The eight barrier: *The new protein must confer a selective advantage to bacteria.* This is a very controversial issue since it is difficult to establish *ex-ante* whether a given protein that enters a metabolic network can indeed confer a selective advantage. The most recent knowledge on ecosystem dynamics is still too weak to propose reliable models of the risks associated with the single variables at play (Bertolla and Simonet [1999]; Nielsen *et al.* [1998]).

5. DOCUMENTED CASES OF HORIZONTAL TRANSGENE INTROGRESSION

Currently, a systematic study on the comparison between transgenic plants and bacteria genomes is still unavailable. This kind of study would allow an inventory of the transgene introgression cases through HGT in open field trials. Some studies that are limited to the comparison of small gene sequences, have allowed us to document six certain cases of HGT introgression, although none of these involve genetically modified plants (Nielsen *et al.* [1998]). However, the research authors are aware that these results do not shed any light on the non occurrence of HGT or indeed whether HGT does occur but rather the experimental techniques used are inadequate. Current knowledge regarding the relationships between different bacterial species, the processes involved in the HGT and soil ecology is lacking, in order to draw definitive conclusions (Bertolla and Simonet [1999]; Nielsen *et al.* [1998]).

A number of laboratory studies addressing the issue of bacteria transformation caused by transgenes produced no definitive results (Gebhard and Smalla [1999]). It is unquestionable that by placing the DNA of the transgenic plant in direct contact with a culture of soil bacteria the stable incorporation of transgenes can be observed, provided that the sequence homology between the capturated DNA and that of the recipient bacteria (Gebhard and Smalla [1998]; Kay *et al.* [2002]; Nielsen *et al.* [1998]). Thus, it seems that the degree of heterology is the main barrier to HGT. However, could this actually be an effective barrier in nature? It may be right to be doubtful, given the immense number of microorganisms capable of horizontal gene transfer and the extremely dynamic genomes of bacteria. Moreover, as the transgene insertion in the plant genome requires the use of bacterial sequences, one cannot rule out that the transgenic organism genome could include a homologous sequence allowing the last barrier to be overcome. It would seem then more realistic to believe that the lack of evidence is due to the unsystematic and extemporary way in which studies have so far been conducted. These studies should also consider other issues, related to HGT, such as the persistence of extracellular transgenic DNA (Pietramellara *et al.* [2006]).

Moreover, the problem could be much more complex than we can imagine. For instance, HGT has been observed to involve not only nuclear genes, but also mitochondrial genes, therefore opening up a new horizon of research: "Does HGT ever occur on a large scale, leading to the horizontal acquisition of most or all of a mitochondrial genome, and/or of many nuclear genes [...]? How do genes move from one plant to another sexually unrelated plant? Is HGT driven predominantly by potential vectoring agents such as viruses, bacteria, fungi, insects, pollen or even meteorites or by the transformational uptake of plant DNA released into the soil? Or even by unrelated plants occasionally grafting together?" (Bergthorsson *et al.* [2003]). Researchers are unable to answer these questions.

6. INTROGRESSION: A PROBLEM OF INTELLECTUAL FRAMEWORKS

Researchers generally rely on natural barriers that inhibit introgression when debating environmental safety of GM crops. However, an incontrovertible fact emerges from this review, in that, natural barriers can indeed be crossed. As Brian Johnson effectively comments: "we need to move on from asking whether gene flow takes place, to investigating what happens when and where it does" (Adam [2003]). The discussion then moves on to the actual risk entity and the possible specific consequences of the phenomenon.

As mentioned aforehand, in order to deal with the risks, uncertainty and ignorance inherent in this problem, we have to globally reconsider the issue of environmental safety of GM crops in open fields as a complex and controversial issue requiring different disciplinary approaches. Moreover, each approach should have its own intellectual framework, its methodologies, and its specific aims (Sarewitz [2004]; Giovannetti [2005]).

The key focus of the open debate on the very existence of the phenomenon as well as the risks implied by introgression consists of different modalities of conceiving and dealing with a substantial lack of knowledge of the interactions between GM crops and the ecosystems that host them. This lack of knowledge is fundamental, as different choices can be made both in terms of production and the use and diffusion of GM crops with potential environmental damage.

In order to understand the different terms that appear in the review, it would seem relevant to keep in mind a classification of the different definitions of lack of knowledge, relating to different decision making modalities (Smith and Wynne [1989]). One speaks of *risk* when the main variables of the problem are known and the respective probabilities of different outcomes are quantified. *Uncertainty* is associated with a situation in which the main variables of the problem are known, but the quantitative incidence of the relevant factors is not and it is therefore impossible to assign different probabilities to different events. Lack of knowledge is defined as *ignorance* when even the main variables of the problem are unknown and therefore the probabilities of negative outcomes are also unknown. Finally, *indeterminacy* has to do with the substantial dependence on the disciplinary framework in which different kinds of scientific knowledge emerge. The disciplinary framework itself is, in turn, embedded in a network of factors, such as, the aims of the disciplines themselves and the socio-cultural and political-economical background, which determine research directions.

GM crops depend on science in (at least) three ways: their production, diffusion and use, safety and their regulation. These three distinct phases which are all equally crucial correspond to three different modes of scientific research: the *innovation science* (Wynne, quoted by Jasanoff [1990]) and the *precautionary science* (Ravetz [2004]) corresponding to the first two phases, the *regulatory science* (Jasanoff [1990]) and the *post-normal science* (Funtowitz and Ravetz [1993]) corresponding to the latter. These research modes are interlinked with traditional disciplinary distinctions, such as ecology, population biology, toxicology, molecular biology and genetics.

Innovation science is the scientific research that is fashioned to conceive and realize new technological products. In this context, emphasis is on the capacity to control and determine specific biomolecular properties which are useful both for those who produce them and those who use them. The aim of the scientist is reflected in a mode of reasoning based on linear cause-effect relationships (the insertion of a specific gene determines a specific advantage) between a limited or limitable number of variables. The interpretative scheme that best suits this approach is based on reductionism and mechanicism, in that, the system-organism is controllable and modifiable because, even if complex, it is separable in elementary subsystems, whose dynamics is much simpler and from which the properties of the whole can be deterministically deduced, that is predicted.

Precautionary science involves the understanding and the management of the possible negative consequences of technoscientific progress, such as the use of matter and energy resources, the creation of new technological products and their introduction on a large scale. In this framework, the focus is on the complexity of the interactions between the organisms involved and their environment. In this case the approach is systemic, that is focused on relationships as founding elements and the reasoning is typically based on highly non-linear causal links, such as retroaction mechanisms, dependence on initial conditions etc. GM organisms are typically interpreted in this case as *processes*, that is, their constant and inevitable relationship with the environment in which they are inserted and live.

Finally, *regulatory science* and *post-normal science* are directly involved in the decision-making processes. The former is essentially carried out with the *innovation science* approach (in some cases even by the same people) differing from the latter in that disagreement (indeterminacy) and the provisional character of the produced knowledge is normally eliminated by an authoritative legitimation from above. This means the 'legitimate experts' are gathered in committees that have the last word and the extended public do not have their say. On the contrary, the latter embraces a systemic approach and a provisional and indeterminate research quality by making the complexity of the interactions between science and policy explicit. Indeed, facts are uncertain, values are in dispute, stakes are high and decisions are urgent in most situations including the current one. This is the post-normal science scenario. Instead of the closure system by a legitimation from above, this model is based on the idea of normative decision as a *creative process* that implies the involvement of a civil society and in which scientific knowledge is just one of many.

Bearing these new elements in mind, it appears evident that scientists who are engaged in the production of GM organisms and are therefore involved in *innovation science*, will tend to apply linear ways of thinking and use methods for reducing the problem to sub-problems characterized by a small number of relevant connections. Fundamentally, this entails evaluating the possible consequences in terms of *risk assessment*. The quantitative evaluation of a problem implies, in fact, the ability to break down a problem into multiple factors in order to know all the relevant variables and quantify the probabilities that the overall system "GM crop-ecosystem" may evolve in different ways. An example of this way of proceeding is the Stewart classification of GM crops in relation to the risk of vertical introgression (Stewart *et al.* [2003]). In this framework, the introgression phenomenon is indeed divided into discrete *steps*, that is, the barriers, which can be separated from one another and independently analyzed. Indeed, each barrier depends on a limited number of variables and interactions and a probability of being crossed can be assigned to each. Given this scenario, the *innovation science* approach, which is based on control and *ad hoc* manipulation, entails implementing specific counter-measures in order to lower the single probabilities. The 'barrier-counter measure' mechanism applied for dealing with the possible negative outcomes reflects the linear way of thinking and the mechanism of *trial-and-error* that are utilized when realizing the benefits. In this case, the lack of knowledge and information is conceived of and dealt with by its maximum quantification, that is, in terms of *risk* or at least as *uncertainty* (as defined by Smith and Wynne [1989]), it is temporary and essentially under control, it can be controlled compared with its possible consequences.

On the contrary, in the precautionary approach, which we hope to use in conjunction with the innovation framework, the way of proceeding is essentially systemic and it challenges the idea of subdividing the problem and cutting off many of the interactions at play. Therefore feasibility, efficacy, absence of collateral effects and feedback mechanisms are disputed, by means of this approach. In the precautionary framework, lack of knowledge is associated with the complexity of the non linear relationships between organisms and environment and it is therefore mostly conceived of as *ignorance*, the condition in which the variables of the problem are unknown, thus, the possible outcomes are also unknown. The very idea of associating a given probability for a given barrier is also discussed since it is based on a way of reasoning that does not take into account many interactions and mechanisms which are still to be investigated. Another systemic objection is based on the idea that low risk negative outcomes do not necessarily correspond to a given low probability. Indeed, when correlated to the endless entity of the possible case record, even to a low probability of an outcome corresponds an actual inevitability over relatively small temporal scales.

7. METHODOLOGIES TO DETECT OUT-OF-NORM EVENTS

Similarly, the two approaches differ in terms of detection methodologies. Indeed, the latter also depend on the various ways of reasoning and experimental procedures. Using a typical *innovation science* approach the differences in the behavior of GM organisms moving from the laboratory to the open fields are considered as marginal. In addition, the detection methodologies and the experimental results are considered as automatically extendible from the controlled situation to the open field. Interestingly enough, in the case of the monarch butterfly (Losey *et al.* [1999]), researchers involved in GMOs have reversed this line of argument *ad hoc*, giving rise to some perplexity (Jesse and Obrycki [2000]; Stanley-Horn *et al.* [2001]; Wolt *et al.* [2003]; Jasanoff [2005]).

The introgression issue is particularly interesting in this regard as the detection methods of the actual cases themselves are in dispute with the consequences of this kind of controversy. The latter is very significant when the stakes grow higher, as in the 2001 case of a possible vertical transgene introgression of a native variety of corn in the region of Oaxaca, in Mexico where GM crops had been banned since 1998 (Quist and Chapela [2001]). The main scientific objections made by the *innovation science* researchers to the article published in *Nature* by David Quist e Ignacio H. Chapela of Berkeley University, were focused on their experimental procedure, overall considered as inadequate in terms of the genetic engineering standards, and therefore their conclusions were dismissed as irrelevant. Scientists working on the systemic approach, even though recognizing some ingenuity in the used methodologies, found the Quist and Chapela conclusions interesting as they could lead to useful new information and indications as to ecosystem behaviors in general. Consequent to the controversy, *Nature* withdrew its support of the article and Chapela lost his tenure at Berkeley. Analogous charges against opponents of the research were directed as belonging, in different ways, to the industrial lobby of biotechnologies (Monbiot [2002]). What matters to us, is the evaluation of the scientific dispute in terms of the different disciplinary and methodological approaches, incommensurable with one another (Sarewitz [2004]), rather than ideological dichotomy.

Discussion regarding the identification of relevant cases and detection methodologies is very significant, as the finding of out-of-norm events, that is, highly unlikely or theoretically impossible phenomena, depend on these factors. In the *innovation science* approach, lack of knowledge of the phenomena that can lead to out-of-norm events is insignificant until the phenomena themselves actually occur. Once these events are known, the aim of the research is to deal with the situation by looking for a *a posteriori* counter-measure. In the decision-making process, this entails minimizing the probability of rejecting developments that turn out to be harmless. On the other hand, in the *precautionary* approach, lack of knowledge is relevant, regardless of the actual occurrence of these events. In the process of decision-making, this would imply minimizing the probability of accepting developments that turn out to be harmful. In this context, indeed, the identification of out-of-norm events is essential, as it contributes to delineate the boundaries of ignorance about the issue at stake.

8. OVERCOMING THE CONTROVERSY: HOW TO MAKE IMPLIED VALUES EXPLICIT AND WEIGH THEM UP

Finally, let's move from the analysis of the controversy to ways of overcoming it, in order to make actual choices as to the regulation of GM crops. As aforementioned, when decisions are urgent in the *regulatory science* approach, a restricted group of experts is given the power to close the controversy, based on scientific advice *weighted on* social-ethical and political-economical considerations. The introgression issue is again emblematic in this respect. Even if this could actually happen, that is, if the probabilities of it happening were medium high, as in the case of vertical introgression, the actual risk for biodiversity associated with introgression would be barely known in its specificity. This lack of knowledge can, in turn, be interpreted and dealt with in different ways, according to different approaches and it leaves room in the decision-making arena for values elements which transform the biotechnology problem into a biopolitical controversy (Nuti [2007]).

A clear example of this shift is the case of the Nuffield Council on Bioethics committee which, as aforementioned, in 2004 suggested that introgression of genetic material into wild species of potatoes in biodiversity protected areas does not justify a ban when the phenomenon occurs in Southern countries, weighting the risk of unknown development over the urgency to intervene against the denutrition problems that afflict those countries. This line of argument is based on a dichotomy between ethics for the

Northern Hemisphere of the World, where one has the luxury of assessing new technologies on the basis of epistemic considerations, and ethics for the Southern Hemisphere of the world, based on a more pragmatic pressure to act. This dichotomy corresponds to *ethics of innovation*, in which reflecting upon risks and uncertainties is marginal compared with practical needs. More precisely, in this scenario, a single pressing ethical principle is invoked – dying from denutrition is unallowed – and based on this principle not only is it justifiable to close the debate on risks and uncertainties and ignorance, but it is also more responsible. On the other hand, a *precautionary* ethical approach is based once more on a systemic way of thinking, in which the relationship between science and ethics is complex and inextricable. Cognitive uncertainty corresponds to and it is strictly connected with the incommensurability of the plurality of different ethical views emerging from different social and cultural contexts and dictated by different needs and interests. These different approaches to the subtle relationship between scientific research and ethics clearly emerge from a recent article by Silvia Francescon on agri-food biotechnologies (Francescon [2006]). In this paper, the Author analyzes the ethical, political, economical and social approaches of the biotech innovation science to the problem of world hunger, based on reductionism and linear thinking. This scenario is then challenged by comparing it with a precautionary approach, systemic in its essence, based on associating different technologies, emerging from local cultures, manageable in a decentralized way and naturally integrated in their surrounding natural, cultural and social environment.

In conclusion, the search for a well-defined scenario based on univocal answers on the issue of environmental risks of transgene introgression coming from GM crops in open fields, brings forward the awareness of the essentially provisional character of scientific knowledge and its substantial dependency on interpretation schemes, methodologies and disciplinary contexts. This awareness involves the idea that each scientific research modality, with its aims, interests and values, is able to produce a coherent body of knowledge that is relevant for understanding and facing the problems under consideration. This awareness is defined as the principle of excess of objectivity (Sarewitz [2004]). This radical indeterminacy of scientific knowledge can be perceived as an upsetting predicament to be eliminated by a process of crediting a scientific authority, as in the case of *regulatory science*, but it can also be embraced as a precious resource to nourish an open creative decision making process, in which facts and values are explicitly articulated and weighted up by using participatory methods, as in the case of *post-normal science*. One needs, in fact, to embrace complexity, to accept the necessity of debating about different incommensurable approaches (Colucci-Gray [2006]) and to reflect upon the inconclusive character of scientific knowledge *tout court*.

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ACKNOWLEDGEMENTS

The authors gratefully acknowledge Camillo Vellano and Guido Badino for critical reading of the manuscript. This study was supported by grants from the Regione Piemonte included in the Integrated Program of Sustainability Education (PIES) 2006 and from personal research fund (G.B.) of Aosta Valley University.

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