The Impact of GMOs in Agroecology: Can You Fool Mother Nature?

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“[T]here are known knowns; there are things we know that we know.
There are known unknowns; that is to say there are things that, we now know we don't know.
But there are also unknown unknowns – there are things we do not know we don't know.”

—United States Secretary of Defense, Donald Rumsfeld

1. Abstract

Agricultural use of Genetically Modified Organisms (GMOs) has spread prodigiously throughout the globe. These crops were introduced in 1996 with a modest planting of 1.7 million hectares. By 2011 hectarage under planting with GMOs had reached 160 million. (Khush, 2012) Increasing 94-fold in just sixteen growing seasons "makes biotech crops the fastest adopted crop technology in the history of modern agriculture." (James, 2011) Figure 1 below displays this explosive growth.

Two camps exist in bitter opposition over their use. One sees GMOs as the potential solution to growing food insecurity and sustainability-related agricultural issues. The other sees them as a possible Pandora's Box that could unwind the fabric of our food webs.

A great deal of attention has been paid to the potential effects of direct consumption of GMOs by humans. Relatively less has been paid to possible ecological impacts. This paper looks at the potential issues of gene flow (the transmission of genetically modified (GM) traits) into other species, the impacts of GMOs on terrestrial and soil organisms, and the potential for mitigation. It wades through the available data and finds some promising findings, but raises more questions than it answers. GMOs are in their infancy in terms of agricultural time scales. We may eventually determine that they are indeed safe and desirable additions to our agricultural systems, but I believe we're currently working without a net.

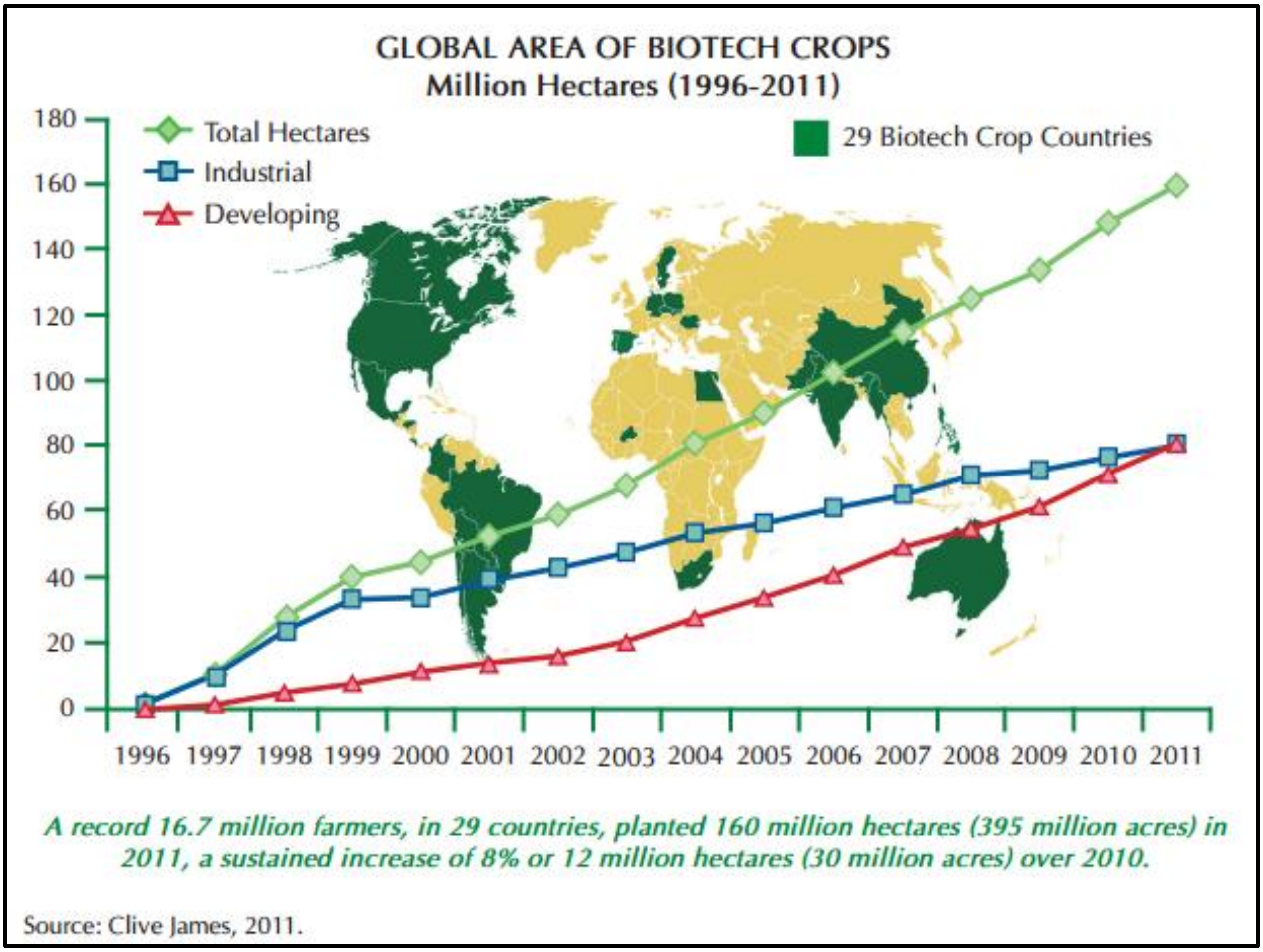

Figure 1 - Growth in GMO Planting Hectarage (James, 2011)

2. Introduction

GMO foods have been in the spotlight recently, largely due to the failed Prop 37 effort in the State of California, which would have required firms to label foods which included GMOs. Proponents of the initiative claimed health concerns to be the impetus of the bill and believed that disclosing which products included GMOs would give consumers the opportunity to make informed decisions. The debate did not touch on ecological factors.

The use of GMOs suggests questions under a number of headings. Ethical considerations around the prospect of "playing god" and the propriety of claiming ownership over a species abound. Economic impacts get tangled up with the ethical questions as we consider whether modification is being pursued for the benefit of the few in the form of corporate profits, or for the many in the form of discoveries sought for social and environmental benefits. As mentioned earlier, human health impacts from the direct consumption of these products is an important concern. Ecological impacts, both those caused by the presence of GMOs, and those brought about by the related changes in employed growing techniques, are also concerns. These questions then lead us to the arena of governance. How should governments regulate these plants? Should we treat GMOs the same as their conventional analogs, or should they be held to higher standards? Or, should they not be allowed at all? This paper explores the ecological impacts of GMOs, but it is important to note that the aforementioned issues cannot be resolved in a vacuum. For example, the optimal economic solution may have disastrous costs in human or environmental terms.

Potential impacts from GMO plants can be placed in two groups: direct ones which would involve things like the transmission of modified DNA to wild species, and indirect impacts such as those caused by farming methods which vary from conventional or organic ones. Table 1 below lists a number of these risks. The potential direct effects of gene flow to wild relatives are reviewed in the next section.

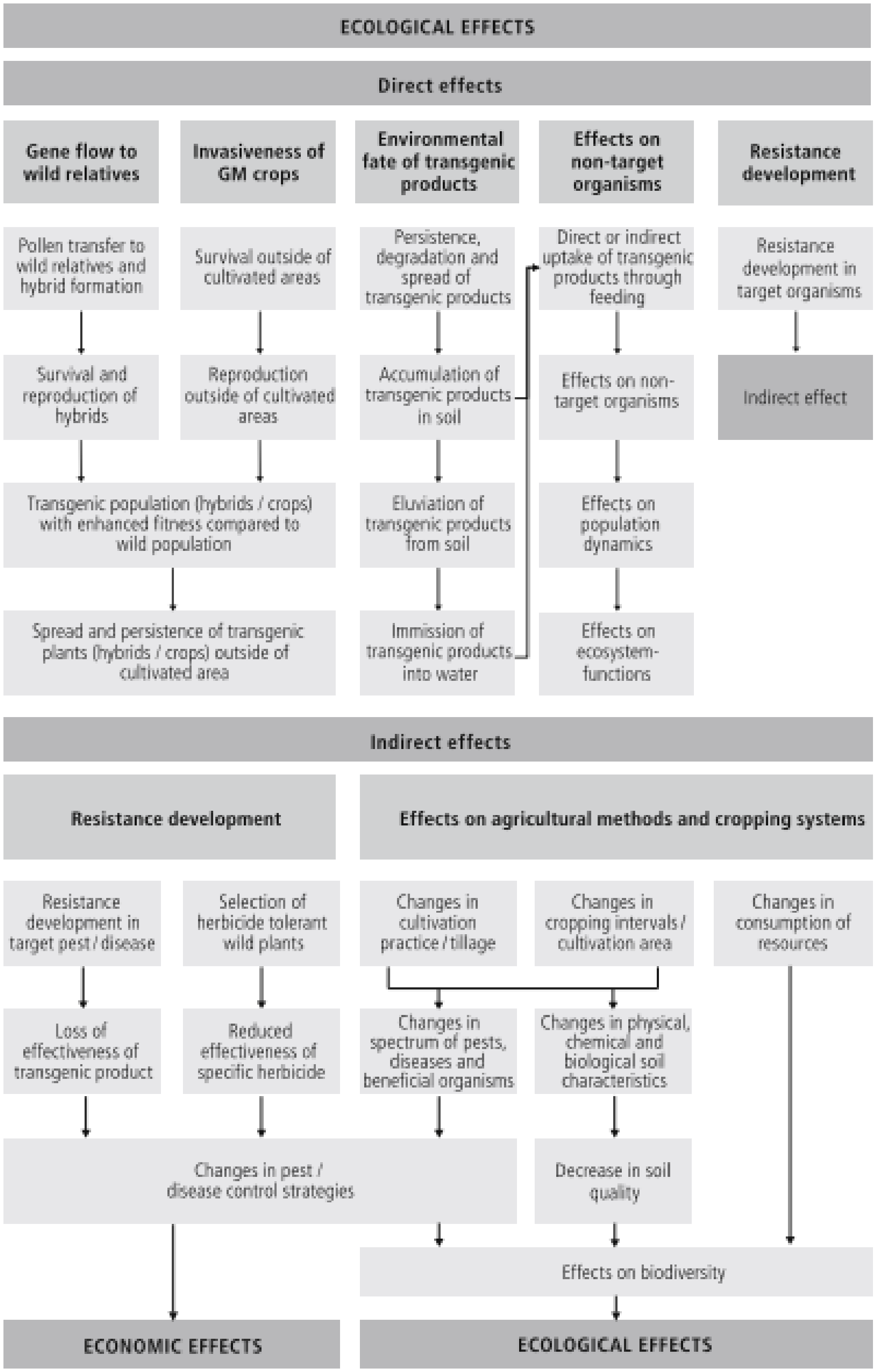

Table 1 - Direct & Indirect Effects of GMOs (Sanvido, Romeis, & Bigler, 2007)

3. Concerns of Gene Flow in GMO Plant Cultivation

The potential impacts of GMO traits include gene flow, dispersal and various impacts to non-target species. (Motavalli, Kremer, Fang, & Means, 2004) Figure 2 below provides a visual representation of the potential impacts of GM crops.

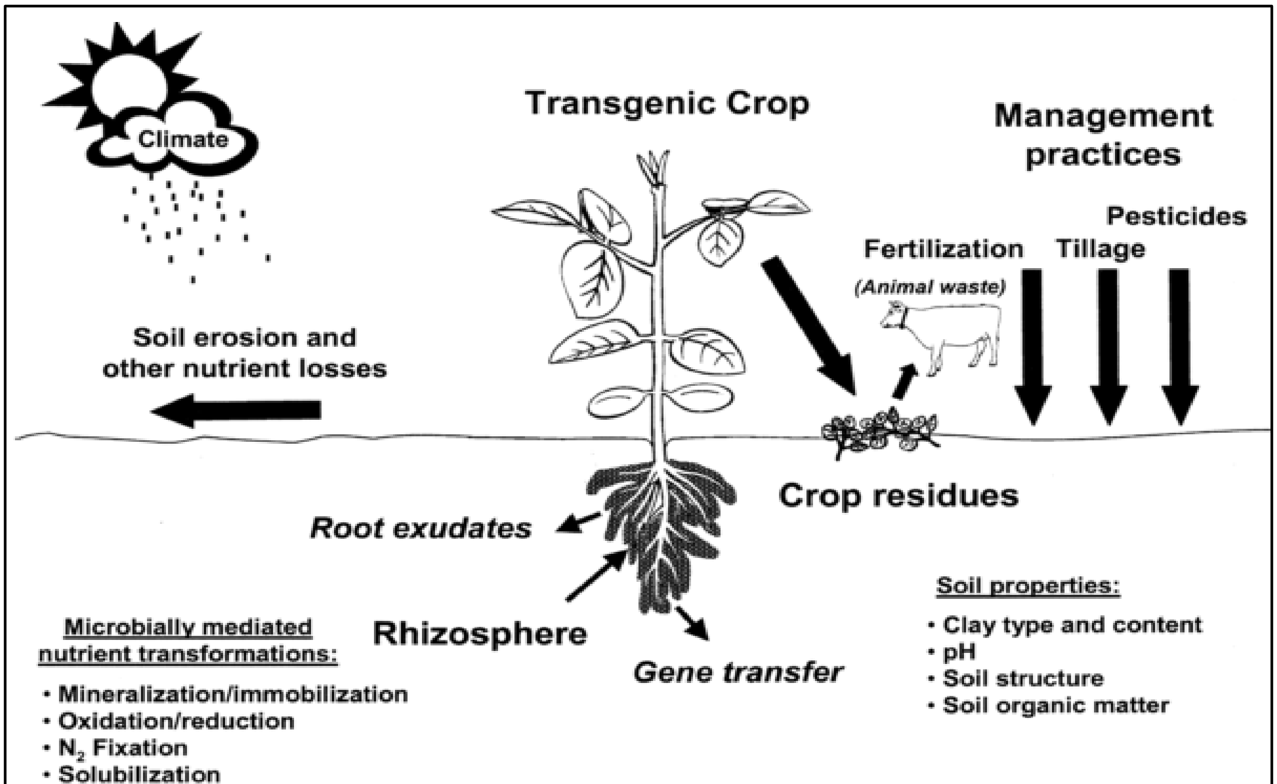

Fig. 1. Potential nontargeted direct and indirect effects of transgenic crops on microbially mediated soil nutrient transformations.

Figure 2 - Potential Direct & Indirect Impacts of Transgenic Crops (Motavalli et al., 2004)

A. Gene Flow

Pollen from agriculture plants can be delivered to its weedy neighbors by a number of methods including wind, water, animal and insect. If the recipient of the pollen is closely related to the crop, hybridization can occur. Through this process, non-native DNA could be passed from GMO plants to wild or weedy species. The result of this is known as gene flow, "a complex process embracing population dynamics, genetics, and the flow of genetic information via pollen and seed dispersal."(Richter & Seppelt, 2004) This would place the GMO traits into the wild and out of human control. This could lead to genetic assimilation, in which crop genes replace wild ones, and demographic swamping, where less fertile hybrids are the result. (Haygood, Ives, & Andow, 2003) In the case of genetic assimilation, gene flow could lead to broad dispersal of the transgenes, which might have far reaching ecological impacts. Demographic swamping could lead to reduced fitness of members of an ecosystem, thereby upsetting species richness and diversity, and possibly driving species to extinction.

One study of gene flow looked at the ability of traits to disperse beyond the fields in which they had been planted. Researchers utilized transects of 800 meters in length to direct the search for GM traits. In year one, they found the traits along those transects up to a maximum distance of 400 meters from the fields. The following year, gene flow was detected at the limits of the study areas. (Beckie & Warwick, 2003) This suggests that at least some modified genes have the ability spread prodigiously. This is one of a number of studies I reviewed which begged the question of why so short a timeline? Research budgets are always limited, but a full doubling (and possibly more) in distance of these traits from their source, in one year, seems cause for additional research. How far might it travel over a longer timeline? Are there mitigating factors that might keep the study population from spreading widely, an ecological island like a mountain range or desert, or can we expect these genes to be assimilated into a the wild population across a broad area? Also, why didn't they extend the measured transects in year two to see how far out they could detect the traits they sought? It seems this is another study that prompts more questions than it answered.

A number of other studies found similar concerns. Scientists determined that farmers might have more trouble managing weedy rice due to the acquisition of herbicide resistance, or increased seed production, and that the GM crop might become suitable to a wider realized niche. (Lu & Snow, 2012) A different study found that weedy and wild relatives received genes from cultivated relatives and that this posed a potential ecological threat. (Chen, Lee, & Song, 2004) The European Environment Agency has suggested that Oilseed rape is a high-risk crop for gene flow to wild relatives, and that low levels of gene flow will reach long distances from the farms they originated from. (Eastham, Sweet, & Gee, 2002) This makes it difficult, if at all possible, to isolate transgenes. None of these studies provides assurance that gene flow will not occur or even that it can be reasonably contained. This begs an important question. Do we understand and can we quantify the risk in human, environmental and economic terms of gene flow from GM crops? What problems might these create for the ecologies of agricultural fields and their surrounding areas?

A study of feral[1] populations of Oilseed Rape found that outcrossing in one season had caused up to half of the offspring of some plants to include genetic material from other plants. (Eastham et al., 2002) It further noted that two other studies had determined that a GM variant of oilseed rape, which had been engineered for herbicide tolerance, was not any more persistent than its convention competitors. (Eastham et al., 2002) It seems they're trying to walk back the initial comment with the second one, but saying that the GMO varieties are no more persistent or invasive than their competition feels like glass half-full commentary at best and wishful thinking at worst. If they're no more persistent, aren't they also no less persistent? The same study went on to suggest that introgression of GM traits into some wild relatives was likely. (Eastham et al., 2002)

B. Impacts to Soil and Terrestrial Organisms

Bacillus Thuringiensis (Bt) variants are some of the most widely planted GM species. Studies of these plants have found that their use can increase productivity, while reducing damage from pests. (Qaim & Zilberman, 2003) (Table 2 below shows the dramatic reduction in pesticide use from a similar study.) They are also considered to be relatively safe for most non-target plants and animals, due to the need of

[1] A feral population is one that has transitioned from domesticated to wild. In the case of plants, this consists of volunteer plants which are generated from the seeds of mature crops, or their progeny. ("Feral," 2012)

high pH levels and specific proteases to turn ingested material into active toxins. (Oliveira, Castro, Capalbo, & Delalibera, 2007)

	2002-03		2004-05		2006-07	
	Bt	Conventional	Bt	Conventional	Bt	Conventional
Insecticide use in kg/acre	2.07*** (2.65)	4.17 (3.37)	2.05*** (2.68)	4.19 (10.48)	1.22* (1.41)	1.55 (1.51)
Yield in kg/acre	658.82*** (393.64)	490.86 (335.88)	742.94*** (327.62)	550.52 (291.22)	841.65*** (356.00)	589.93 (335.09)
Net revenue in Rs./acre	5294.22*** (8117.19)	3132.99 (6773.89)	4921.83*** (6290.90)	2152.08 (5476.80)	7120.82*** (7654.80)	4181.26 (7563.07)
Number of observations	133	301	165	300	317	56

Mean values are shown with standard deviations in parentheses. Data was obtained from three rounds of a farm panel survey carried out in the states of Maharashtra, Karnataka, Andhra Pradesh, and Tamil Nadu. Details of the sampling framework are discussed elsewhere[17].

*, **, *** Mean values are different from those of conventional cotton in the same year at a 10%, 5%, and 1% significance level, respectively.

Table 2 - Comparison of insecticide use, yields, and net revenues between Bt and conventional cotton plots in India (Subramanian & Qaim, 2008)

International law requires that GM plants are studied for their impacts on non-target organisms, but ecotoxicological tests typically focus on a limited number of non-target species (Oliveira et al., 2007) which opens the possibility for significant impacts to be missed in testing. If a GM crop negatively impacted fitness of a keystone species, what would the outcome be?

Gastropods, microarthropods, and mycorrhizal fungi were studied for unintended impacts due to exposure to Bt maize. Researchers found that the transgenic crop was not toxic to these studied insects in the 3 to 4 months that they were studied. (De Vaufleury et al., 2007) This is another case of positive results found over what seems too short of a time line to be considered conclusive. Are we to assume that farmers will only plant these crops for one season and then rotate them out? Even so, a full year's study would seem a minimum starting point and one of multiple years seems warranted as the farmers that are growing these crops are likely using them for their potential economic benefits and as such are not likely to rotate crops often, if at all.

Bt toxins have been extensively studied for their impacts on non-target organisms, but few studies have considered soil ecology. (Oliveira et al., 2007) Soil invertebrates are keystones to sustainable agriculture as they breakdown dead organic matter making it once again available as nutrients for other organisms. Without this vital part of the natural ecosystem, nutrient cycling slows. In response to this, farmers increase their use of fertilizers, thereby increasing the negative impact on soil and water ecosystems as only small amounts of the chemicals that are sprayed are taken up by their targets. (Baligar & Bennett, 1986) The rest ends up in the soil, air, or water, where they cause a variety of problems. (Blevins, Wilkison, Kelly, & Silva, 1996; Hairston, 1988; Robertson, 2000) Bruinsma,Kowalchuk and Veen add weight to this argument by highlighting "the failure of most studies to assign a definitively negative, positive or neutral effect to GMP (Genetically Modified Plant) introduction." (Bruinsma, Kowalchuk, & Veen, 2003)

GMO potatoes have not been found to have directly detectable effects on the rhizosphere, but when leaves from these plants were introduced to the soil, protozoan populations suffered significant losses. (Griffiths, 2001) If the leaves are detrimental to soil microbiology, what would happen to these fields after a number of years of the species' presence? Are we to assume that the leaves will be collected to mitigate this impact, thereby removing an important soil amendment? Another experiment in the same study found that GNA-producing potato lines consistently altered the physiological profile of the rhizosphere microbial community at harvest, but that the effect had disappeared by the second season.(Griffiths, 2001) It's unfortunate that they only studied this for two years as it seems this is another case where the results need to be validated over a number of seasons. If the same result was realized with a study of five or more years, then I think I would feel comfortable accepting the results. As it stands, they need to be questioned. I would recommend a longer study and larger trials. I suspect the larger the size of the field, the more likely the results would be different as it would be more difficult for individuals outside of the test plots to repopulate the fields, should that be part of the cause of recovery from the existing study. I would also suggest monitoring for immigration and emigration in future studies to see what impact (if any) those factors have. It's possible that the negative impacts of the GM plants were overcome by r-selected reproduction, but this suggests an increased likelihood of extinction in years with extreme circumstances.

Glyphosate, Monsanto's broad-spectrum herbicide, has become the best-selling product of its kind. (Binimelis, Pengue, & Monterroso, 2009) Glyphosate has been an incredibly effective herbicide for nearly half a century, but it is not without fault. The product is billed as a non-concern for plant resistance due to its point of application, (Binimelis et al., 2009) and Stanley Robert and Ute Baumann add that this gene would not be able to pass via pollen transfer to weedy relatives, but they add that there are plenty of Brassica weeds which might be able to hybridize with engineered variants of Rapeseed. (Robert & Baumann, 1998) That scientists see plant resistance, to the herbicide, as highly unlikely seems positive, but references to the contrary abound. (Duke & Powles, 2008; Heard et al., 2003; Powles & Preston, 2010) More importantly, the potential for hybridization still exists. We need to better understand what the possibility of hybridization is and what dangers it might bring at a time when we're allowing the rapid overtake of our agricultural systems by these technologies.

Sanvido adds that, "Target pests could develop resistances against the insecticidal proteins produced in GM crops resulting in a loss of effectiveness of the transgenic product." (Sanvido, Romeis, & Bigler, 2007) This suggests that the GM traits will force the hand of evolution by putting pressure on the target species. Individuals that are susceptible will die off, leaving behind those that are able to survive in the presence of the trait. This raises the specter of super weeds or super bugs which are more virulent than the one's which farmers were initially concerned with. This idea stokes fears of cataclysmic collapse in crops akin to the late blight which struck Ireland in the 1840s, but it's possible that this technology could be the solution, rather than the cause, of such problems.

Spread of glyphosate resistant creeping bentgrass was studied by planting plugs of transgenic and conventional bentgrass. Spread of these species were then measured along transects as a proxy of fitness. The conventional and transgenic lines showed no difference in their ability to spread beyond the field's borders. (Gardner, Danneberger, Nelson, & Danneberger, 2012) The results suggest that there's no greater chance that the transgenic line will be a better competitor than the control lines, but this seems cold comfort. If the goal is to confine the genes to a controlled area, being equally fit seems a poor control mechanism. Another study looked at "long-term" application of glyphosate (6 years) which found microbial communities to be altered. (Dick, Lorenz, Wojno, & Lane, 2010) I find it a bit disturbing that it took us thousands of years to arrive at conventional agricultural practices, but that some consider a six year study a long-term look into glyphosate use. I hope that longer term studies are in progress.

Alternately, a similar study of Oilseed rape (OSR), which had been genetically modified for herbicide resistance, did not show an increase its invasive potential. These transgenic lines performed worse than conventional lines. (Sanvido et al., 2007) As we might expect, GM crops will vary in fitness levels according to their specific permutations and the conditions in which they are grown. A fine line may be crossed in which a less fit competitor becomes better adapted simply due to conditional variation between seasons.

C. Mitigation Potential

What stands in the way of widespread dispersal of modified genes? Some scientists suggest that GM plants may be at a disadvantage when growing in areas that are free of the pest they were engineered to defend against, as the energy used to produce the toxin they are bred for reduces the energy available for competition against plants which do not have this energy requirement. (Chapman & Burke, 2006) This assumes that gene flow has occurred to the extent that the traits would have escaped the range of the pest it was intended to combat, or that the crops would have been planted in an area that it was not intended to be used in. Neither of these assumptions feels reassuring. When considering the enormous cost to bringing a GM crop to market, one must assume that the intent is to plant it widely. Moreover, economics incent farmers who are sowing GMO crops to ignore recommended planting patterns. (Hyde, Martin, & Preckel, 2000) Given this scenario, who is policing the matter? One might assume that the foxes are running the henhouse and that the cats are in cahoots!

Efforts are made to mitigate gene flow. Scientists look to contain the spread of GM traits, but there are no hard and fast rules for determining how competition will play out in nature without testing it. Regional variation adds complexity as niche complementarity tells us that what we expect often isn't what we get. Favorable alleles should tend to win the day, but do we know enough to predict other outcomes in differing circumstances? Models attempt to account for significant factors, but how will they account for the variables which play into the success (or lack thereof) of differing species? It is difficult, if at all possible, to account for discontinuous population structures and the possibility of occasional long-distance dispersal, but both of these factors are common for most species. Discontinuous population structure can reduce dispersion, but might also open the door for greater dispersion as an allele entered a new area where it was better fit to compete. The occasional long-distance dispersal feeds the opportunity for the trait to find suitable areas and possibly engender metapopulations. These push and pull factors make it incredibly difficult to model the dispersion of GM traits. (Chapman & Burke, 2006) Figures 3 & 4 below display the explosive growth of GM crops, both in total number of hectares grown worldwide (Figure 3) (which has since doubled), and the percentage of the most common crops with GM traits in U.S. agriculture (Figure 4). These visuals display the magnitude of potential risk to ecosystems inherent in our current system. While these plants may prove to be safe, it appears we've thrown caution (and pollen) to the wind.

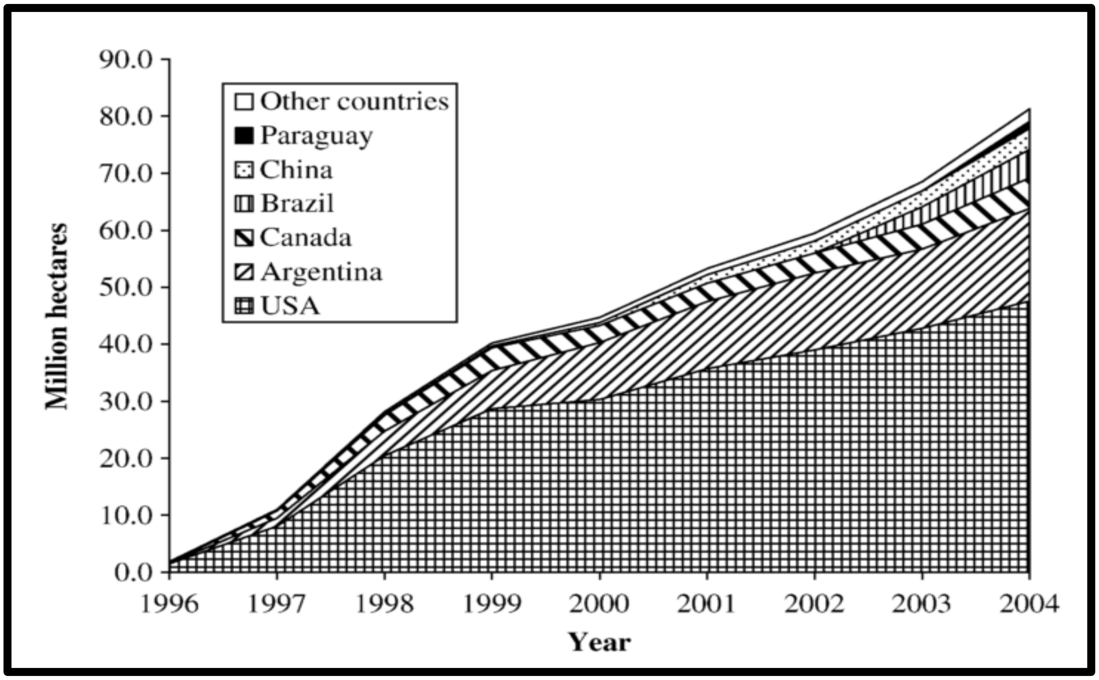

Figure 3 - Proliferation of GM Crops 1996-2004 (Chapman & Burke, 2006)

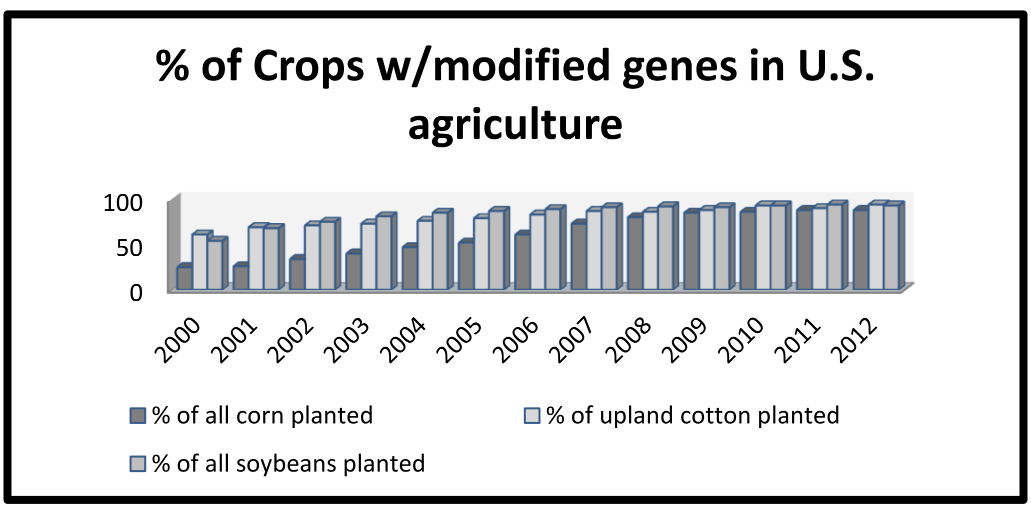

Figure 4 - Percent of US crops with modified genes 2000-2012 (USDA, 2012)

4. Conclusions

While promising findings have been made, it seems there is still much to learn about the risks and opportunities of GMO plants. Many studies have suggested GMOs to be harmless, but more recent ones have identified potential ecological risks. (Dana, Kapuscinski, & Donaldson, 2012) Soil microbiology was once ignored, or assumed to be safe, but long-term use of glyphosate to tolerant cropping (GTC) systems have recently come under question for possible negative impacts to soil microbiological communities and the processes which they support. (Dick et al., 2010) If this is true, then it's undoubtedly causing problems with nutrient cycling and it may be affording conditions for plant diseases to prosper. As mentioned earlier, extant studies have typically focused on just a handful of organisms and they've typically lasted for no more than a couple of years. This suggests the need of a greater emphasis on studying the long-term impacts that these technologies have on our agroecological systems. They may prove to be just what we need to solve the problems of a growing, ever hungrier population, but they might still be just the opposite.

Fortunately, there's hope for containing genes with good farming practices. Sanvido suggests that "the simplest way for farmers to reduce selection pressure placed on weeds is to avoid planting continuous glyphosate-resistant crops and to annually rotate the herbicides used." (Sanvido et al., 2007) Repetitively grown monocultures are the norm on today's farms, but that practice is changing as farmers learn the benefits of crop rotation. (Cardinale et al., 2011) This trend, coupled with Sanvido's findings, suggest there may be hope for practices which might be better able to contain GMOs than those techniques which are more commonly employed today.

It's not surprising that the public debate has focused on the human health impacts of GMOs, but the impacts in the fields could lead to far larger impacts on us as a species. With more than 160 million hectares deploying GMO plants, agriculture might be in a situation akin to climate change. Even if we stopped planting GMO seeds immediately, the genes would continue to exist for years to come. And, unlike carbon dioxide and its analogs, we don't appear to have a great handle on what the impacts of GMOs might be. With that, I think it's worth taking another look at Figures 1 & 3 and considering whether you live in a country that's bearing a disproportionate risk in relation to the adoption of GM crops.

I hope that the future of GM crops is in the prevention of future crises like the Irish Potato Blight, while ensuring that subsistence farmers are able to produce enough food for their needs through challenging climatic circumstances, but I fear the unknown-unknown is a larger component than we're led to believe and that the risks may still outweigh the benefits. In time, good science will tell.

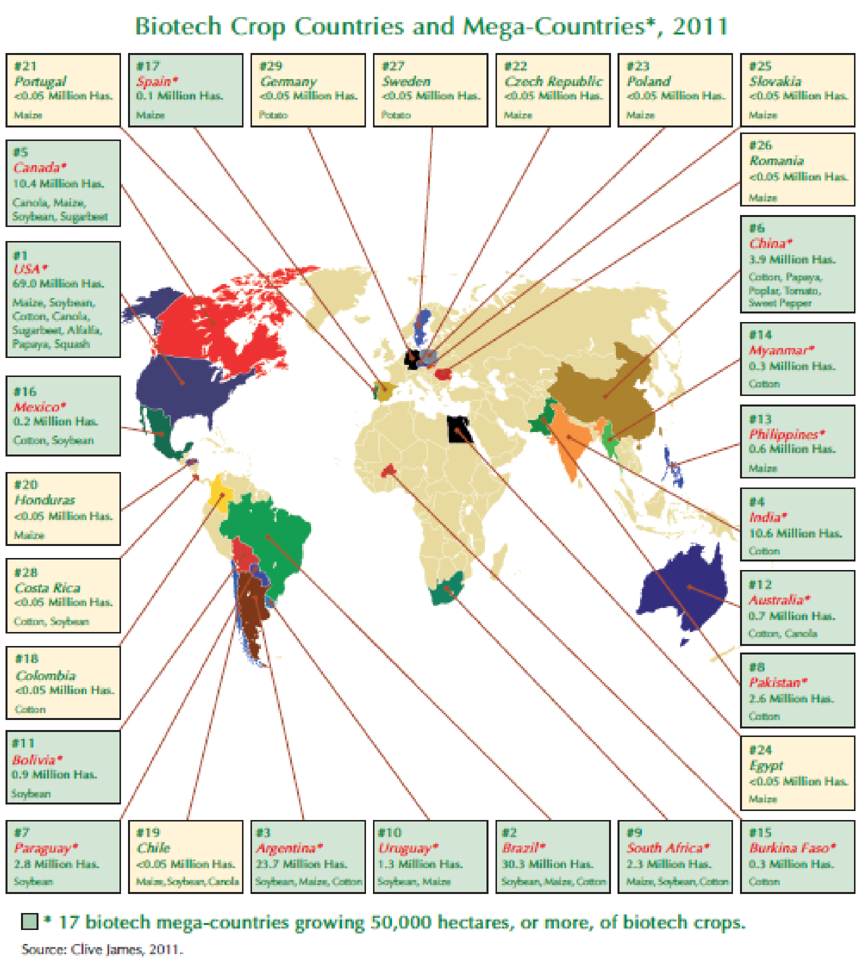

Figure 5 - Global Map of Biotech Crop Countries and Mega-Countries (James, 2011)

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