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Potential Environmental and Socioeconomic Impacts of Herbicide Resistant Cassava

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Introduction

The purpose of this report is to investigate the potential environmental and socio-economic benefits and costs of glyphosate resistant cassava. Glyphosate resistant crops (also referred to as glyphosate tolerant) have been rapidly adopted by a number of crop producers because they simplify and/or reduce the cost of weed management. Glyphosate resistant crops also provide external environmental benefits by promoting reduced tillage agriculture, decreasing erosion and increasing soil health. Reduced tillage has allowed some farmers to reduce farm machinery use, decreasing fuel costs and reducing carbon emissions. However, glyphosate resistant crops also have some environmental costs, potentially leading to increased use of herbicides and environmental contamination. They may also adversely affect agricultural ecosystems, reducing farm biodiversity or conferring herbicide resistance to wild plant species through gene flow. Increased global use of glyphosate likely contributes to the evolution of herbicide resistant weed varieties that cannot be effectively controlled with glyphosate. In the long-term, this may offset some of the benefits of glyphosate resistant crop use, potentially increasing production costs, soil tillage, and the use of other more toxic herbicides.

Because transgenic[a] glyphosate resistant cassava is not currently in use, literature on its potential environmental and socioeconomic costs and benefits is limited. Therefore this report draws on the literature for glyphosate resistant crops that are in current use, including maize, soybeans, sugar beets and canola (rapeseed). The literature indicates that socioeconomic and environmental impacts of glyphosate resistant crops differ by crop-type,

Some Common and Unresolved Questions

What are the constraints to herbicide use in cassava production?

Herbicide is rarely used in cassava production, despite some demonstrated economic advantages.

Do environmental costs and benefits vary significantly in different agroecological zones?

Studies across zones for environmental impacts are thin, so agro-ecological factors remain uncertain.

How do potential benefits of glyphosate resistance compare to the benefits of other genetic modifications?

Genetic modification might improve cassava production in a number of ways (e.g. increased yields, drought, disease and pest resistance, nutritional content).

What are the long-term implications for glyphosate use and farm weed management?

Glyphosate resistant weeds have become more prevalent in recent years.

What are the primary benefits of adopting glyphosate resistant cassava?

A primary benefit is reduced weeding requirements for family members or hired labor.

Are there other risks associated with formulations and application practices?

Some glyphosate formulations contain other chemicals, which have negative health and environmental impacts. Small-scale cassava farmers in developing countries may not have the skills to utilize best practices in application.

[a] We use "transgenic" throughout this report to refer to crops with genetically engineered genetic material, other terms include: genetically modified organism (GMO), genetically modified (GM), genetically engineered organism (GEO), and biotech.

agroecological conditions, production systems and local regulatory structure. Some benefits and costs associated with other glyphosate resistant crops may not be applicable to glyphosate resistant cassava.

The report is divided into six sections. Section 1 provides an overview of worldwide transgenic herbicide resistant crop adoption, including a discussion of the potential benefits of transgenic crops in the developing world. In Section 2, we review the current status of cassava production, focusing on Sub-Saharan Africa. Section 3 discusses the literature on the economic impacts of currently cultivated glyphosate resistant crops, as well as the few *ex-ante* studies on herbicide resistant cassava. We discuss the toxicity of glyphosate and health impacts on humans and animals in Section 4. Section 5 reviews the environmental literature focusing on changes in herbicide use rates, reduced soil tillage, the evolution of glyphosate resistant weeds, gene flow from transgenic crops, and effects on biodiversity. In Section 6, we address the controversy surrounding the use of glyphosate and glyphosate resistant crops and discuss some claims from glyphosate and glyphosate resistant crop detractors.

Section 1: Transgenic Herbicide Resistant Crop Adoption

Global Transgenic Glyphosate Resistant Crop Adoption

In 2009, herbicide resistant crops made up 83% of all transgenic crops

Glyphosate is a broad-spectrum herbicide that, due to its effectiveness for weed control and its relatively low environmental toxicity, has become the world's leading agrochemical.[1] A number of factors have contributed to the current prominence of glyphosate for weed management. The largest contributing factor was the commercial release of herbicide resistant (herbicide tolerant) crop varieties in 1996, which greatly increased global glyphosate demand. In 2000, the patent on glyphosate expired, allowing for generic manufacture and substantially lowering the cost to consumers.[2]

Table 1: Introduction of Glyphosate Resistant Varieties in the United States by year

Crop Type	Year of Introduction[b]
Soybean	1996
Canola	1996
Cotton	1997
Maize	1998
Alfalfa	2005
Sugar Beet	2007

Source: Duke & Cerdeira, 2005

Since the commercial introduction of herbicide resistant crops in 1996, adoption and use of herbicide resistant varieties has steadily grown. In 2009, thirteen years after introduction, herbicide resistant crops represented roughly 83% of the 330 million acres planted with all transgenic varieties worldwide.[3,c] Of the total worldwide acres planted with herbicide resistant varieties, 52% consisted of herbicide resistant soybeans and 24% of herbicide resistant maize, while only 5% was herbicide resistant canola, and 3% herbicide resistant cotton. Due in part to later release on the market, herbicide resistant alfalfa and sugar beet have not been as widely adopted on the global level. Although crops resistant to other herbicides do exist, the vast majority (estimated 90%) of herbicide resistant crops currently in use are glyphosate resistant varieties.[4]

Glyphosate resistant varieties have been widely adopted in some countries and for some crops. In the United States, herbicide resistant varieties of soybeans, cotton, and maize represented 94%, 75% and 72% respectively of total US acreage

[b] Commercial introduction coincides with deregulation of the transgenic variety in question
[c] This number includes herbicide tolerant varieties stacked with multiple transgenes(e.g. traits conferring insect resistance)

devoted to each crop in 2011.[5] In Argentina, 99% of soybean area and 70% of the hybrid maize area was planted with herbicide resistant seeds.[6] In Brazil, herbicide resistant soybeans represented 70% of total area devoted to genetically modified crops.[7] These three countries have been the largest adopters of transgenic crops, accounting for 78% of global transgenic crop acreage in 2010, although not all of this acreage was for herbicide tolerant crop varieties. [8] See Appendix A for further information on where transgenic crops are currently cultivated.

In addition to Argentina and Brazil, a number of other developing countries have also adopted glyphosate resistant crops. In South Africa, the country with the greatest acreage of transgenic crops in Africa, glyphosate resistant crops made up 85% of total soybean acreage and 100% of cotton in 2010.[9] In Paraguay, Bolivia and Uruguay, glyphosate resistant varieties represented 100%, 85% and 90% respectively of total soybean acreage.[10]

Transgenic Crops can Benefit Farmers in Developing Countries

> Transgenic crops have been shown to benefit farmers in developing countries, but benefits are variable and existing literature is limited

The literature generally suggests that transgenic crops have economic advantages in developing countries when compared to conventional crops. However, research on socioeconomic impact is limited and shows variable results. This section describes the literature on the effects of transgenic crops in developing countries and for smallholder farmers.

A 2010 study of the worldwide benefits of transgenic crops reported that farmers in developing countries earned 55% of total worldwide farmer benefits. Most cultivated primarily insect resistant cotton or herbicide resistant soybeans. Farmers in developing countries paid less for adopting transgenic technology than farmers in developed countries as a percentage of total farm income gains.[11] Factors that prevented smallholder farmers from adopting transgenic crops included information, credit, and infrastructure constraints, as well as local regulations and high seed prices.[12]

Another review of economic benefits in developing countries from 2006 also reported "positive, but highly variable, economic returns to adopting transgenic crops".[13] The report noted that a variety of factors influenced economic benefits in developing countries, including input markets, regulation, and intellectual property rights laws. The report also concluded that some concerns about equity in the use of transgenic crops may be unfounded. The distribution of benefits from adopting transgenic crops did not appear to differentially favor large farms. Furthermore, consumers, producers and biotech companies shared the economic surplus resulting from transgenic crop use.[14]

Limitations of the Developing World Transgenic Crop Literature

An IFPRI review of research conducted from 1997-2007 concluded that benefits varied greatly but on average, transgenic crops provided economic benefit to smallholder farmers in developing countries. However, the study also highlighted several limitations in the existing research. Major issues included limited research scope and coverage, both in terms of geographic areas and crop types (most studies covered insect resistant crops), and a scarcity of ex-post impact studies. Another issue was that studies did not consider the possibly differential impacts of transgenic crops for different socioeconomic groups (e.g. across genders). Some of the reviewed studies contained design problems such as selection, measurement and estimation bias. Others had insufficient sample sample sizes. [15] Qaim's review (2009) of the impact of transgenic crops also noted a lack of literature on socioeconomic impact of transgenic crops in developing countries, including research on impacts on rural employment and incomes.[16]

Section 2: Current status of cassava production and potential for glyphosate resistant cassava

Glyphosate Resistant Cassava May Reduce Farmer Costs

Cassava is an important staple crop in many areas in the developing world, and particularly in Sub-Saharan Africa. Hand weeding is one of the major costs of cassava production and insufficient weeding can significantly lower yields.[17] On cassava farms where weeds are currently controlled by herbicide, glyphosate resistant cassava may reduce herbicide costs. On farms where farmers use hand weeding for weed control, glyphosate use could reduce labor costs. Glyphosate resistant cassava varieties have the potential to increase cassava yields in cases where labor or time constraints prevent regular weeding. *Table 2* summarizes some of the primary potential benefits and costs of transgenic herbicide resistant cassava. These potential costs and benefits will depend largely on production methods, adoption rates, and local conditions.

> Glyphosate resistant cassava could reduce labor demands, and in some situations, reduce herbicide costs

Table 2: Key Potential Benefits and Costs of Glyphosate Resistant Cassava

	Potential Benefit	Potential Cost
Production	• Reduced labor requirements for weeding • Increased yields on farms with weeding labor constraints	• Higher seed cost • Requires herbicide purchase for benefits
Environment	• Reduced erosion, improved water retention, improved soil health due to reduced tillage • Decreased short run use of more toxic herbicides	• Selective pressure for glyphosate resistant weeds • Increased potential for glyphosate pollution • Potential increase in use of more toxic herbicides in the long run
Labor	• Increased labor productivity	• Decreased employment

The following sections discuss current regional cassava production practices, emphasizing weed control, to contextualize the potential economic benefits and costs of glyphosate resistant cassava. We focus primarily on Sub-Saharan Africa, as this region represents over half of worldwide cassava production.

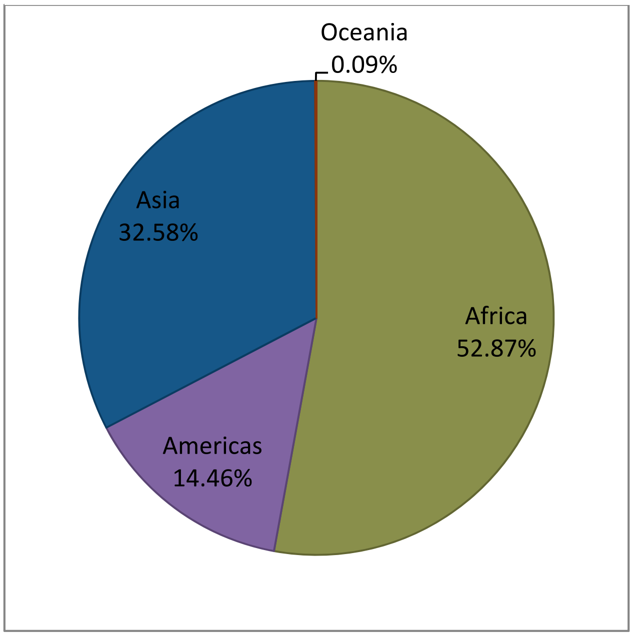
<u>Sub-Saharan Africa Produces Over Half of the World's Cassava</u>

> In 2010, 53% of global cassava production was in Africa

According to FAOSTAT, roughly 230 million tons of cassava was produced worldwide in 2010. Of the total, Africa, Asia and the Americas accounted for 53%, 33% and 14% of production respectively (see *Figure 1*). Thirteen of the top 20 cassava producing countries were in Sub-Saharan Africa, led by Nigeria, which produced the most cassava worldwide.[18] Much of the information on cassava production in Africa comes from the Collaborative Study on Cassava in Africa (COSCA), conducted from 1989 to 1997 in the Democratic Republic of Congo, Ivory Coast, Ghana, Nigeria, Tanzania and Uganda.[19] Farmers in Africa planted an estimated 12 million hectares with cassava in 2009.[20] Cassava was more frequently a cash crop in West Africa than in southern and eastern Africa.[21] Cassava production in Africa has increased in recent years,[22] beginning in the 1990's in West Africa, in the 2000's in eastern and southern Africa. In 2009, cassava in Africa was primarily produced for human consumption, but FAOSTAT reports that a substantial portion was also used for animal feed (35%).[23,d]

[d] This proportion is based on the FAOSTAT Food Balance Sheet from 2009. Data from some countries is not available and is thus not included in the proportion.

Figure 1: Cassava production by region in 2010



Source: FAOSTAT

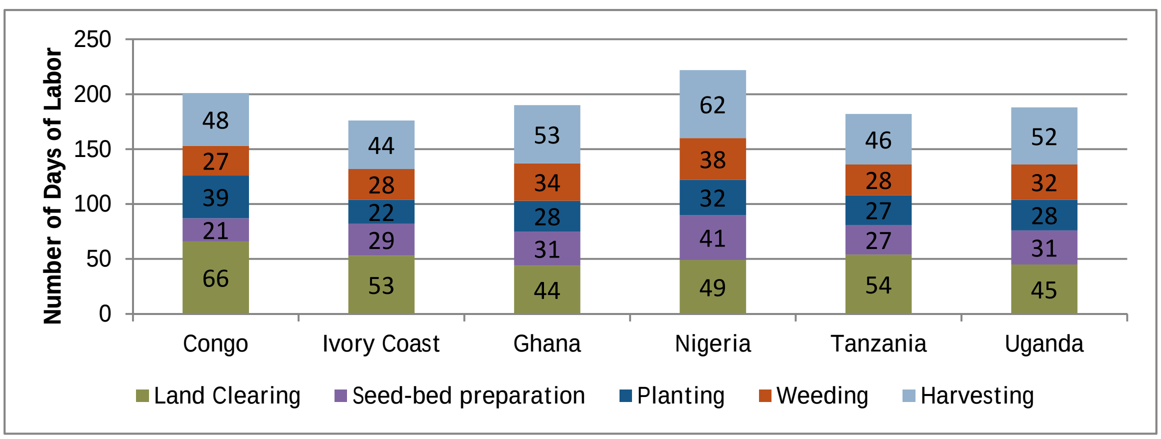
Weed Control, Which is Primarily Done by Hand, Represents a Major Cassava Production Cost

Studies in several countries in the 1970's estimated that uncontrolled weed growth resulted in a 46-95% yield loss.[24] Some consider poor weed management to be one of the most important production constraints for cassava.[25] Early weed control was one of four "pillars" to improve cassava crop management in a study in Uganda and Kenya.[26]

Hired labor was the most common input used in cassava farming.[27] The COSCA Phase II study reported 40% of farmers hired labor for cassava cultivation.[28] The proportion of hired labor in relation to family labor varied considerably between the six COSCA study countries, with farmers in the Congo supplying all labor from within the family and farmers in Nigeria hiring labor on 77% of cassava fields.[29] Weeding made up 14% to 19% of total labor requirements for cassava production in the six COSCA countries.[30] In the Fermont (2009) study, 36% of farmers hired labor, primarily for weeding, and low access to labor appeared to reduce yields.[31] In a more recent study in Nigeria, 69.7% of farmers hired labor for cassava production in the Obubra Local Government Area, with labor constituting 65.2% of the production cost.[32]

Higher yield varieties, adopted by commercial cassava farmers, require more labor at harvest than lower yielding varieties, which has shifted labor limitations from weeding to harvesting in commercial farms.[33] In Nigeria, harvest labor shortages were a more significant constraint than weeding labor shortages.[34] Since cassava can be left unharvested for months, the harvest labor constraint did not affect small scale and subsistence farmers.[35] In all COSCA countries, weeding required fewer labor days than land clearing and harvesting (see *Figure 2*).

Figure 2: Days of Labor per Activity



Source: COSCA study[36]

Herbicide is an Effective, but Underutilized Weed Control Method for Non-glyphosate Resistant Cassava

> Herbicide weed control is economically advantageous for current cassava varieties, but is rarely used by small scale farmers

Studies in Sub-Saharan Africa have shown that herbicides are more cost effective than hand weeding, however, a 2011 study found that only 5% of smallholder farms used herbicides on any crop.[37] Large commercial farms used herbicide at higher rates to reduce labor costs.[38] Farmers' perceptions of cassava as a weed tolerant crop may reduce all types of weed control on cassava. Prioritization of other higher value crops also influences weed control on cassava.[39] A 2011 study on the benefits of herbicide in Africa attributed low rates of herbicide adoption to a lack of training and information dissemination.[40] According to Melifonwu (1994), herbicides can be an effective weed control for cassava and reduce labor requirements, but resource limited farmers may not be able to afford them or have the skills and knowledge to use them appropriately.[41] Field trials in the late 1970's in Nigeria found metobromuron, prometryn, flumeturon, Primextra (atrazine and metolachler), diuron and diuron with paraquat to effectively and economically control weeds in cassava fields.[42]

Glyphosate can be used on non-glyphosate resistant cassava plots as a pre-emergence herbicide. A 2001 study comparing hand weeding to herbicide use (with and without various cover crops) in Benin reported glyphosate weed management benefited farmers. Glyphosate application resulted in higher net benefits (27.7% higher than weeding twice and 89.9% higher than weeding five times), higher benefit-cost ratios (particularly for velvet bean and velvet bean/kudzu intercrops) and returns to labor that were 40.3%-47.5% higher than plots that were hand weeded.[43] Even when the authors considered that farmers would need to purchase glyphosate on credit (which they estimated would increase costs by 10%), glyphosate remained economically advantageous compared to hand weeding.[44] Glyphosate resistant cassava would increase the flexibility of glyphosate application, as famers could apply the herbicide after planting cassava.

Several studies in Nigeria have reported variable rates of herbicide application on cassava fields. In a study on weed control in Kogi State, 37.6% of surveyed farmers used herbicides on cassava and herbicide users had a 14.6% yield advantage compared to farmers not using herbicides.[45] Statistical modeling indicated that herbicide was significantly associated with higher yields. Surveyed farmers reported that herbicide use was feasible for smallholder farmers, but lack of information, training and access may inhibit adoption. Cost of equipment, fear of crop damage, and aversion to change may also discourage herbicide adoption.[46] The authors recommended that young farmers receive education on herbicide use and intercropping, but acknowledged that increased productivity through herbicide use will not benefit farmers

> Cassava Production in Nigeria
>
> At 37,504,100 metric tons in 2010, Nigeria produces more cassava than any other country in the world (FAOSTAT). It is most commonly eaten as *gari* in both urban and rural areas and by both low-income and by high-income households. Cassava consumption increased almost 40% from 1961 to 1998 and the COSCA study found that 80% of rural Nigerian households ate cassava. In cassava producing households, an average of 11.6 % of cash income came from cassava and 40% of the COSCA sample households earned income from cassava; both figures are higher than for any other individual food crop. As cassava is often a cash crop in Nigeria, farmers use more hired labor than in other African countries, harvest earlier, and face significant labor constraints for harvesting (Nweke, et al 2002).
>
> Studies find wide variation in herbicide use on cassava plots in Nigeria, from 2% to almost 40%, depending on the study and location within the country. Weeding required less labor than harvesting (38 and 62 days, respectively) and women were responsible for weeding 34% of plots (Nweke, et al 2002).

without adequate markets and processing infrastructure.[47,e]

Another Nigerian study based on a survey from 2005 in Anambra state described much lower levels of herbicide use. Thirty-three percent of farmers surveyed were aware that herbicide could be used on cassava, but only 2% reported using it.[48]

A third Nigerian study in Abia State found 15.6% of a sample of small-scale farmers used herbicide on their cassava plots, but usage varied between zones from 1.4% to 25.3%. The study also surveyed farmers about constraints to herbicide adoption; 45.7% of farmers surveyed identified lack of awareness as a constraint. Farmers also identified lack of technical or application knowledge (16.5%), high cost (14.9%), non-availability (14.5%) as constraints to adoption. [49]

Cassava Production in the Rest of the World

> Cassava production in Asia and the Americas is more commercialized than in Africa

While Africa leads the world in cassava production, Asia and the Americas also produce cassava. In 2010, four of the top ten cassava-producing countries were in Asia (Thailand, Indonesia, Vietnam and India). India had the highest cassava yields in the world in 2010.[50] Ninety–four percent of the world's cassava exports in 2007 came from Asia, led by Thailand exporting 18 million tonnes.[51] According to a 2000 study, Asia's cassava management was relatively intensive compared to Africa or Latin America, but weed control remained primarily manual. Herbicide use was increasing, particularly in Thailand, but also common in China and Indonesia. The report predicted a 7% yield increase through improved weed management.[52] Production systems varied, but manual laborcost increases have led to increased farm mechanization.[53]

Cassava production in the Americas is concentrated in Brazil, which was the second highest producer of cassava in the world in 2010. Paraguay ranked 19th and Colombia 22nd. Although Brazil has strong national research programs, investment in cassava has been inadequate in the region as a whole, as the crop is grown and consumed primarily by the poor.[54] While most weed control in the region was achieved through hand weeding, herbicide use became increasingly common on commercial farms. [55,56] As in Asia, the number of agricultural laborers in South America has declined, increasing the need for less labor intensive production methods, such as mechanization.[57] While the area planted with cassava in Latin America remained mostly stable in the last 25 years, yields increased substantially in some areas.[58] Most farmers have not adopted the highest yielding technologies, constrained by economic and environmental conditions, including lack of access to inputs.[59] As in Africa, farmers may prioritize other crops when allocating time and resources, as cassava will produce yields even with poor management.[60] In 2009, more cassava in the Americas was used for animal feed than for human consumption.[61]

Herbicide Resistant Cassava Has Not Been a Priority in Transgenic Cassava Development

> Herbicide resistant cassava is likely feasible, but has not been a priority of in biotech research

Despite its importance as a global food crop, cassava has received relatively little research investment.[62] According to a 2002 article, herbicide resistant cassava could benefit medium to large-scale farmers, but not smallholder farmers who may face a number of barriers in purchasing chemical herbicides. As a result, most international aid organizations did not prioritize this genetic trait in transgenic research. Other entities funding transgenic cassava focused on modifying cassava starch qualities, rather than herbicide resistance.[63] In a 2012 article on cassava breeding, herbicide

[e] Another study by the same author in 2008 indicated similar, but slightly lower herbicide use (30.0% primarily used herbicide for weed control and 3.8% used both herbicide and hand weeding).[e] Non-herbicide using farmers primarily cited "high cost" as the reason for non-utilization (72.7%), followed by "operational problem" (19.8%) and scarcity (7.5%).

resistance is not mentioned as a breeding priority.[64] Glyphosate resistant cassava is mentioned as a "medium-term possibility" for controlling weeds in cassava in a Latin American review of cassava production.[65] The authors of the study contend that public-private partnerships would be the best route to development and stress that legal issues and risk may complicate private sector development.[66] A review of cassava production in Asia, predicted that chemical companies, potentially in partnership with public entities, might incorporate herbicide resistance in new cassava varieties, as they would profit from both seed and chemical sales.[67] Researchers view glyphosate resistance as technically feasible, given the past development of glyphosate resistance in other crops.[68]

The International Center for Tropical Agriculture (CIAT) proposes no-tillage cultivation of cassava to reduce erosion and reduce detrimental environmental impact of cassava. However this method is unlikely to be adopted without herbicide tolerant cassava varieties. CIAT has explored transgenic and non-transgenic methods of developing herbicide resistant cassava. Preliminary results of field trials in 2009 and 2010 suggest that one CIAT developed genotype is tolerant of glufosinate-ammonium.[69,70]

Glyphosate Resistant Cassava Labor Changes Could Disproportionately Affect Women

> Cassava weeding is commonly the responsibility of women thus labor impacts of glyphosate resistant cassava may differ by gender

Cassava has sometimes been considered a women's crop, but the COSCA study determined that in Sub-Saharan Africa, cassava fields are more often either jointly owned or owned solely by men. The division of labor by gender depended on the task and the specific location.[71] In the six COSCA countries, women performed most of the weeding in 43% of cassava fields, men did most of the weeding in 34% of fields, and weeding in 23% of fields was performed jointly. Division of weeding labor differed substantially by country. Women were responsible for weeding only 10% of plots in Ghana, but weeded 84% of plots in Congo. In Nigeria, women performed most of the weeding on 34% of cassava fields (see *Figure 3*).

Figure 3: Bulk of Labor Performed by Gender (Proportion of Nigerian Cassava Plots

Source: COSCA Study[72]

Changes in labor markets result from adoption of glyphosate resistant cassava may disproportionately impact women in areas where they perform the majority of the weeding. Reducing women's labor is a benefit where there are more productive uses of their time, but could also hurt women that rely on cassava weeding for employment. The EPAR brief on gender and cassava cropping reported that labor saving technology in Nigeria did reduce cassava labor time, but the technology was generally male owned, and as result the economic benefits accrued largely to men.[73] Furthermore, as cassava becomes more of a cash crop, labor has been shown to shift towards men.[74]

Section 3: Economic Benefits of Glyphosate Resistant Crops

Glyphosate Resistant Crops Reduced Costs for American and Argentinian Farmers

A review of glyphosate-resistant crops in the US reported cost savings for weed control for glyphosate resistant soybeans, maize, cotton, and canola, but these savings were offset by increased seed prices.[75] For example, for glyphosate resistant soybean farmers in the US from 2000 to 2005, herbicide costs decreased by USD$300 million, but seed costs increased by USD$312 million.[76] World market prices for crops with glyphosate resistant varieties have been shown to decline. Qaim &Traxler (2005) calculated the effect of glyphosate resistant technology on soybean prices to be a decline per year of between USD$0.03/t in 1996 to USD$1.96/t in 2001. They estimate the total 2001 increase in global economic surplus as USD$1.2 billion. [77]

A study of glyphosate resistant soybeans in Argentina found considerable cost savings for farmers using glyphosate resistant soybeans. Compared to conventional seed use, farmers increased total factor productivity by 10%, mostly from reducing herbicide costs and costs associated with mechanization (fuel and repairs). [78] The study found that small farms (defined as 27 to 100 ha) benefited more than larger farms, likely due to lower seed prices, as small farms were more likely to buy uncertified herbicide resistant seed. [79] These results are not likely representative of glyphosate resistant crops for small-scale farmers in the developing world. All the Argentinian soybean farms were fully mechanized and used chemical fertilizers and the "small" farms are much larger than the average plot size of non-commercial farmers in much of the developing world. [80]

The distribution of economic benefits between farmers, seed/chemical companies, and consumers varies greatly based on local patent law. For example, a 2005 study of glyphosate resistant soybeans in Argentina found that seed patents contribute more to seeds prices in North America than in South America, leaving North American soybean farmers to accrue relatively fewer of the benefits.[81] Ninety-one percent of the total surplus in Argentina went to producers, while only 21% of the total surplus went to American producers. Glyphosate resistant crops, through increasing yield and lowering prices, can also create indirect costs for non-adopters of the seed and management practices. In the 2005 study, soybean producers in the rest of the world lost an estimated USD$290.6 million as non-adopters. [82]

An Ex-ante Study on Glyphosate Resistant Maize Predicted Benefits in Uganda and Kenya

A previous EPAR analysis using IFPRI's Dynamic Research Evaluation Model (DREAM) estimated the potential impacts of glyphosate resistant maize in Kenya and Uganda. The study predicted total net benefits over 30 years of USD$0.64 billion in Kenya with 70% accruing to farmers, and $0.33 billion in Uganda with 76% accruing to farmers.[83] Gains are the result of reduced labor costs for weeding. However, sensitivity analysis showed wide variation in benefit levels, depending on adoption rates, prices and other uncertain variables. The analysis predicted that some or all non-adopting farmers would experience losses due to decreasing prices. [84]

Ex-ante Studies Predicted Substantial Benefits of Glyphosate Resistant Cassava in Colombia

Researchers predicted glyphosate resistant cassava could produce varied but substantial benefits for farmers in Colombia

Literature on the economic benefits of glyphosate resistant cassava is limited. However, two ex-ante studies examined the potential economic benefits of herbicide resistant cassava in Colombia.[f] Both studies predicted production cost savings from adopting herbicide tolerant cassava varieties, although the magnitude of estimated benefits was very different. Some of

[f] An additional CIAT/IFPRI study using the IMPACT model to determine economic impact in 10 countries found gains in most countries, particularly early adopting cassava producers in exporting countries and consumers in importing countries. This paper has not been reviewed as only the abstract was available. (Creamer, B. & Gonzalez, C. (n.d.) Ex-ante impact evaluation of herbicide tolerant cassava. CIAT and IFPRI. Abstract retrieved from: http://www.danforthcenter.org/GCP21-II/8.GCP21-II.Abstracts/S4%20Agronomy%20&%20Field%20Production/S4%20Oral%20presentations/S04-05_Creamer_a.pdf)

this variation is likely due to differing scales and different assumptions about prices and production costs and the discount rate.

The first study used IFPRI's DREAM, a probabilistic simulation model, to estimate cassava production costs in six regions of Colombia under (1) mechanization of harvesting and planting, (2) conventionally bred high-yield varieties, (3) herbicide resistant cassava with glyphosate weed control, and (4) current practices.[85] The model predicted that glyphosate resistant cassava produced greater cost savings for farmers than other alternatives and led to labor cost reductions of 25%- 42.5% for six different regions in Colombia (34.1% nation-wide). After accounting for supply-shifting price effects, they estimated the present value of producer and consumer surplus for the period of 2002-2016 to be USD$508.1 million with herbicide-resistant cassava. Much of the production cost reduction comes from substituting manual weed control with glyphosate. The authors predicted a reduction in employment of about 25%, but with an accompanying increase in labor productivity. The economic benefits of herbicide resistant cassava in Colombia were predicted to be split between producers and consumers, with 40% of the benefit going towards consumers. The model predicted that non-adopting cassava farmers in other regions would face reduced earnings (USD$43.2 million total). Variability in benefits between the six regions studied indicated that initial resource endowments affected benefit levels. [86]

In the second study, which evaluated the potential benefits of herbicide tolerant cassava for three zones (Highland, Midland, Lowland) in the region of Cauca, Villamarin (2011) compared cassava production costs with glyphosate resistant varieties to costs with conventional varieties, assuming that the main structural difference under the two production systems were differences in the cost of weed management.[87] The model predicted that herbicide resistant cassava would reduce labor costs for producers by an average of 12.6% per hectare. The estimated present value of the benefits from adopting herbicide resistant cassava from 2012-2032 was roughly USD$958,000. Benefits accrued more or less equally to consumers and producers. Zone influenced the costs reductions associated with adopting herbicide tolerant cassava, with the lowland zone showing the highest reduction in cost per hectare (16.6%) and the highland zone the lowest (10.7%).

Sensitivity analysis found that net benefits associated with adoption of herbicide tolerant cassava had high variance, indicating that cassava production in Cauca is relatively risky. After running 10,000 iterations of the model using different assumptions about technology diffusion, market and technology prices, cassava output levels and the discount rate in each zone, 60% of the midland zone iterations, 49% of the of the highland iterations, and 39% of the lowland iterations predicted a net loss after the first year of adopting herbicide tolerant cassava. The factors with the greatest influence on the level of benefits from adoption of herbicide tolerant cassava were output levels and market prices, with the higher cost of herbicide tolerant seed relatively less important. A 10% increase in seed price reduced the net benefits by 3.4% in the lowland zone, 16.1% in the intermediate zone, and 4.4% in the highland zone. In contrast, a 10% increase in cassava output increased the net benefit by 57.3% in the lowland zone, 243% in the intermediate zone and 78.4% in the highland zone.

An Increase in Demand for Cassava Bioethanol may Affect Cassava Production and Prices

Increased demand for cassava may affect economic implications of glyphosate resistant cassava

In addition to human consumption, cassava is also used for animal feed, industrial starch, bioplastics, processed foods, and increasingly, bioethanol.[88] Demand for cassava for bioethanol could increase the value of the crop.[89] An increasing share of cassava production is traded internationally (8-10% reported in 2012), two-thirds of which is exported to China. If demand for cassava continues to grow, it could affect international market prices.[90] One study predicted cassava price increases of 54%-135% under various scenarios of increasing cassava bioethanol demand.[91]

Section 4: Toxicity of Glyphosate and other Herbicides

The toxicity, carcinogenicity and/or mutagenicity of a chemical is explored with studies including animal experiments, human epidemiology and sometimes in vitro cellular research. Toxicity refers to acute systemic effects, while carcinogenicity refers to chronic exposure and long term effects resulting in cancer tumors in tissues or organs. Human exposure to chemicals occurs by ingestion (with food, water or inadvertently), inhalation or dermal absorption. It is worth noting that animal studies may use additional routes of exposure to deliver chemicals to the body, such as gavage or injection, which are not routes by which humans would be exposed in a natural setting. Also, animal studies rely on high dose exposures, often far above those expected to occur to humans in the environment, in order to distinguish health effects in animals more efficiently. Uncertainty factors and extrapolation methods are used to translate results from animal studies into estimates of exposure levels thought to be safe for humans.

When considering human exposure to pesticides as a result of consumption of agricultural crops, it is important to account for uptake or incorporation of chemicals into plants, a process which leaves a fraction of the pesticide in soil, water and/or air with which the crop is in contact. It is also necessary to account for breakdown or metabolism of the pesticide. Plants treated with glyphosate translocate it widely, to their roots, shoot regions and fruit. The compound interferes with the plant's ability to synthesize protein. Because plants absorb glyphosate, it persists in the plant even after washing, peeling milling, or baking. In fact, glyphosate may persist in foods made from exposed crops for up to two years.

Toxicity of Glyphosate

Glyphosate has relatively low toxicity, but may pose minor deleterious health effects on humans

The EPA rates glyphosate as a Toxicity Class III chemical (on a scale of I-IV, with I being the most toxic, indicating that glyphosate may have minor deleterious effects for humans. Measures of toxicity such as the LD_{50} and Reference Doses indicate with fairly high confidence that glyphosate in isolation poses low risk if used at suggested rates. However, glyphosate is not useful as an herbicide in its pure form as it is water soluble. It cannot pass through plant surfaces without the mediation of surfactants. Roundup contains glyphosate mixed with POEA, to allow the solution to pass through the hydrophobic barrier and into plants. And the presence of POEA or other surfactant is thought to have a significant impact on toxicity as outlined below.

Experimental studies on mammals

The reference doses established for acute effects in mammals are relatively high (Table 3). In other words effects are not observed at low doses but rather only at high doses, and thus glyphosate is not considered highly toxic. This is in direct contrast to several currently used herbicides, for which effects occur at extremely low levels – e.g., atrazine, diuron, which are more toxic than glyphosate, and paraquat which is highly toxic. Further, technical glyphosate has very low acute toxicity by the oral and dermal administration routes. It is markedly more toxic by the intraperitoneal route (i.e, gavage, exposure by stomach tube) than by other routes; however, gavage is not a route by which human exposure occurs in any natural setting.

Carcinogenicity of Glyphosate

Glyphosate has been classified as group E (i.e., evidence of non-carcinogenicity), and was downgraded from a previous group C rating (i.e., possible human carcinogen) by the U.S.A. EPA.[92,93] The herbicides most commonly replaced by glyphosate are not widely regarded as carcinogenic either, although data are not adequately conclusive in all cases.

Human Exposure

In a review of 80 intentional ingestion cases (suicide attempts) involving the commercial preparation Roundup (a mixture with 41% glyphosate and 15% POEA polyethoxylated tallow amine as a surfactant), there was evidence of adverse health endpoints in humans. GI distress, difficulty swallowing, and gastrointestinal hemorrhage occurred in many of those exposed, and seven of these cases resulted in death. The presence of the surfactant POEA is thought to play an important role in these poisoning cases. Unfortunately POEA facilitates passage not only across the surface of a plant but also into the human body. Since POEA is considered to be an inert ingredient, it is not regulated as a pesticide, yet it is believed to contribute substantially to health concerns associated with pesticides containing glyphosate.[94]

Eye and skin irritation have occasionally been reported from dermal exposure to glyphosate formulations. But permanent ocular or dermal damage is rare. Inhalation of the compound in spray mist form may cause oral, nasal or throat irritation.

Conditions of use and setting

Labels on pesticides are very specific about safe use and intended conditions. Long sleeves and long pant legs are to be used as protection for applicators during herbicide use, thus preventing much dermal exposure. However if applicators and agricultural workers are wearing lighter clothing (perhaps due to use in warm climates) a significant increase in exposure is expected.

In addition, pesticide exposure to humans varies as a result of changes in temperature, wind speed and wind direction.[95,96] Research by Ramaprsad et al (2009). and Tsai et al. (2005) specifically examines aerial spray drift and links to inhalation risk in communities living in close proximity to pesticide application (between 15 and 200m away). They find that climate, as well as wind speed and direction, affect transport and ultimately influence human exposure levels. Revolatilization of pesticides at high temperatures is also noted by these authors– a potential concern when considering pesticide use in hot climates.

Another factor that can impact exposure and health is adsorption of pesticide to soil, which varies with composition and type of soil.[97] Compounds which are adsorbed are less available for human exposure. But soil quality and composition may change due to agricultural use or practice, which in turn changes adsorption efficiency. Removal of organic matter from soil results in less adsorption of glyphosate on the soil, while more of the pesticide is carried by water or is available for plant uptake and for human exposure. Thus use of pesticides in areas where soil is poor in organic content is of higher concern.

Finally, pesticides introduced to fabric, clothing, bed sheets, and intended to combat pests in the home or field, can come into contact with human skin and be absorbed.[98] Wester *et al* (1996) found that if cloth is wet, even re-wetted after a period of being dry, the pesticides it has been treated with are absorbed by skin up to four times more effectively as they are from dry cloth. This is a secondary concern for our purposes since our focus is pesticide application on crops in a field setting.

Glyphosate is generally less toxic than the herbicides it may replace

The environmental impact of herbicide use depends to some extent on the application rate, but to a larger extent on the toxicity of the herbicide itself and the herbicide it replaces.[99] Most of the literature from countries in the developed world found that that glyphosate was relatively less toxic than the herbicides it most commonly replaced.[100,101,102,103,104]

Location specific information on herbicide use is necessary to evaluate the relative toxicity of glyphosate to herbicides in current use. A preliminary comparison between glyphosate and three herbicides commonly used in Nigeria indicates that glyphosate is relatively less toxic than herbicides in current use (See Table 3).

Table 3: Toxicity comparison between Glyphosate and herbicides commonly used in Nigeria

	Human Carcinogenicity*	**Mammalian Toxicity(Oral)**		**Level of Confidence in RfD*** **
		Acute Toxicity**	Oral Reference Dose (RfD)***	
Glyphosate	Group E- Evidence of Non-carcinogeneticity for Humans	**Low** LD_{50} 4320mg/kg (rats)	**Increased incidence of renal tubular dilation in offspring(rats):** NOEL[a]- 10 mg/kg/day Oral RfD 0.1 mg/kg/day	High
Atrazine	Not likely to be carcinogenic to humans	**Medium** LD_{50} 1780 mg/kg (rats)	**Decreased body weight(rats):** NOAEL[b] 3.5mg/kg/day Oral RfD 0.035 mg/kg/day	High
Metolachlor	Group C- Possible Human Carcinogen	**Medium** LD_{50} 2780 mg/kg (rats)	**Decreased body weight (rats):** NOEL[a]- 15/mg/kg/day Oral RfD 0.15 mg/kg/day	High
Diuron	Likely to be carcinogenic to humans	**Low** LD_{50} >5000 mg/kg (rats)	**Abnormal pigments in blood(dogs):** NOEL[a]- .625 mg/kg/day Oral RfD 0.002 mg/kg/day	Low
Paraquat dichloride	Group E- Evidence of Non-carcinogeneticity in humans	**High** LD_{50} 3-5mg/kg (human) 100 mg/kg (rats)[105]	**Chronic pneumonia (dogs):** NOEL[a]- .45 mg/kg/day Oral RfD 0.0045 mg/kg/day	High

*Source: U.S. EPA, Office of Pesticide Programs; **Source: U.S. National Pesticide Information Center, unless otherwise footnoted; ***Source: U.S. EPA IRIS; [a] No Observable Effect Level; [b] No Observable Adverse Effect Level

Section 5: Environmental Impacts of Glyphosate Resistant Crops

Modern agriculture has often relied on cocktail herbicide application and soil tillage for weed management. Adopting glyphosate resistant crops allows some farmers to use a single herbicide for weed management, changing herbicide use rates. It also reduces the need for weeding, affecting rates of soil tillage and potentially reducing damage due to erosion. Reducing the use of soil tilling machines might reduce fossil fuel use in crop production. Changes in weed farm management practices may have both positive and negative environmental consequences. The following sections discuss the literature on the potential environmental costs and benefits of glyphosate resistant crops, including increased environmental contamination, the benefits of reduced tillage agriculture, the evolution of herbicide tolerant weed varieties, and effects on farm biodiversity. Most studies on environmental impact of glyphosate resistant crops are from the developed world.

<u>Environmental Contamination</u>

Evidence is inconsistent regarding changes in herbicide use rates with glyphosate resistant crops

One major concern with herbicide use is the release of toxic chemicals into the environment. The adoption of glyphosate resistant crops has led to changes in farm herbicide application rates. However, there is conflicting evidence in the literature on both the direction of herbicide application rate changes and on the resulting environmental impact.

A 2000 report from the USDA on herbicide use found that in the years directly after introducing glyphosate resistant soybeans, glyphosate use on soybeans increased and the use of other herbicides decreased, leading to a 10% percent reduction in total herbicide use.[106] Another USDA report two years later reported decreased herbicide use among farmers adopting glyphosate resistant maize and cotton.[107]

However, other studies reported that the adoption of glyphosate resistant crops increased herbicide application rates. A report by the Center for Food Safety concluded that intensity of herbicide use in the US rose for corn, cotton and soybeans from 2002-2007, as adoption of glyphosate resistant varieties increased.[108] Qaim & Traxler (2005) found that after the adoption of glyphosate resistant soybeans in Argentina, herbicide use increased significantly, attributing the increase to herbicide supplanting tillage for weed control.[109] Benbrook (1999) found that herbicide use on glyphosate resistant soybeans was two to five times higher than for conventional soybeans.[110] [g] Another study by Dill *et al* (2008) found that use of non-glyphosate herbicides did not change significantly on maize, cotton or soybean after adoption of glyphosate resistant crops.[111]

The risk of air, water and soil contamination is relatively low with glyphosate

The environmental damage also depends on the ability of a chemical to contaminate air, water and soil. A number of studies claim that the risk of glyphosate in soil and water may be relatively low. Glyphosate has a relatively short half-life in soil (average of 47 days), is broken down by soil microbes and has low soil toxicity.[112,113] Glyphosate also binds to elements found in soil, mitigating the potential of leaching into groundwater.[114] Glyphosate has low volatility and therefore does not likely pose a risk as an air contaminant.[115,116]

Glyphosate Resistant Crops Can Reduce Tillage and Fossil Fuel Emissions

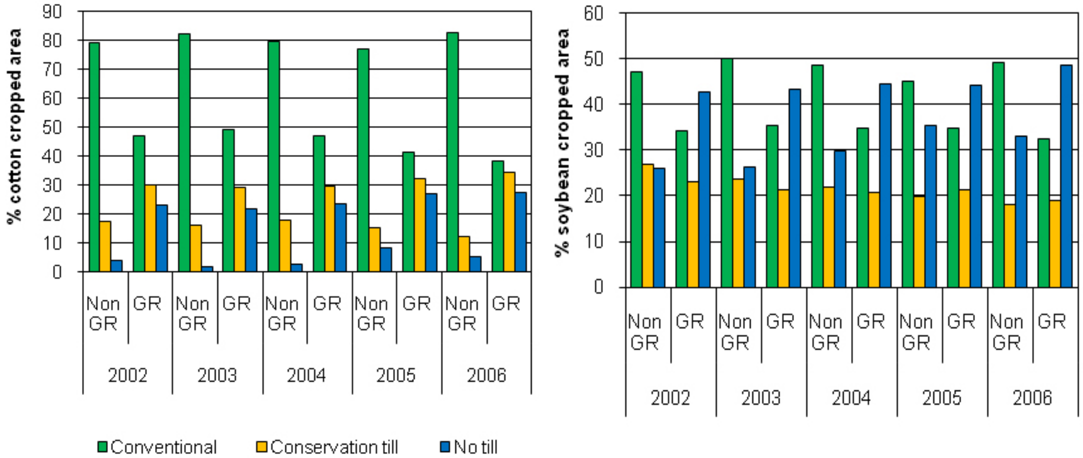
One of the primary claimed environmental benefits of glyphosate resistant crops is that it reduces the need for soil tillage for weed management. Glyphosate resistant crops have allowed increased adoption of no-tillage or conservation tillage farming systems. The environmental benefits of reduced tillage farming systems include reduced loss of topsoil and erosion, reduced leaching of agro-chemicals into water, reduced soil compaction, and improved soil water holding capacity and drainage.[117,118] Reduced tillage systems might also reduce fossil fuel emission and improve soil carbon sequestration.[119]

The 2008 study by Dill *et al* found that glyphosate resistant crop use did correlate with the use of conservation tillage and no-tillage farming among soybean, maize and cotton farmers in the US from 2002-2006, but the effect varied based on crop(See Figure 4).[120]

Conventional tillage was more widely practiced by non-glyphosate resistant variety farmers for maize, cotton and soybeans than for farmers using glyphosate resistant varieties. Conservation tillage, defined as tillage practice that leaves at least 30% of residue on the soil surface, was practiced by similar numbers of glyphosate resistant and non-glyphosate resistant variety adopters among soybeans farmers, but was more commonly practiced by glyphosate resistant maize and cotton variety users. No-tillage farming was more widely practiced by farmers using glyphosate resistant varieties, with the difference most pronounced among cotton farmers. In an Argentinian glyphosate resistant soybean study, 80% of farmers that adopted glyphosate resistant crops used no tillage systems, compared to only 42% of conventional soybean farmers.[121]

[g] Gianessi (2005) argues that the herbicide use rates in this study are not realistic because the comparison treatments would not provide weed control that was as effective or as affordable as glyphosate.

Figure 4: Tillage type for glyphosate resistant and non-glyphosate resistant soybean and cotton adopter from 2002-2006



Source: Dill *et al* 2008

Reduced use of agricultural machinery in crop production might decrease the need for fossil fuel use, potentially reducing greenhouse gas emissions. Brookes & Barfoot (2010) found that the average amount of tillage fuel for herbicide tolerant soybeans was 24.3 liters per hectare compared to 36.5 liters per hectare for conventional soybeans in 2008, a reduction of roughly 33%.[122] The total reduction in fossil fuel use in tractors for tillage was 834.5 million liters from 1996-2008, avoiding an estimated 2,295.3 kilograms of CO_2 emissions from US soybean growers. For the same time period, the authors estimated potential reductions in carbon emissions of up to 38,057 kilograms due to improved carbon sequestration, although they emphasize that this is an optimistic estimate. Emission reduction estimates for Argentinian soybeans and Canadian canola also showed substantial decreases in fossil fuel use and carbon emissions. Qaim & Traxler (2005) found that soybean farmers in Argentina growing glyphosate resistant crops used on average ten liters less fuel per acre than farmers using conventional soybeans.[123] In an ex-ante study on herbicide tolerant sugar beets, Bennet *et al*(2004) identified emission reductions from reduced herbicide manufacture, transport and field operations as the main environmental benefit over traditional crop production.[124]

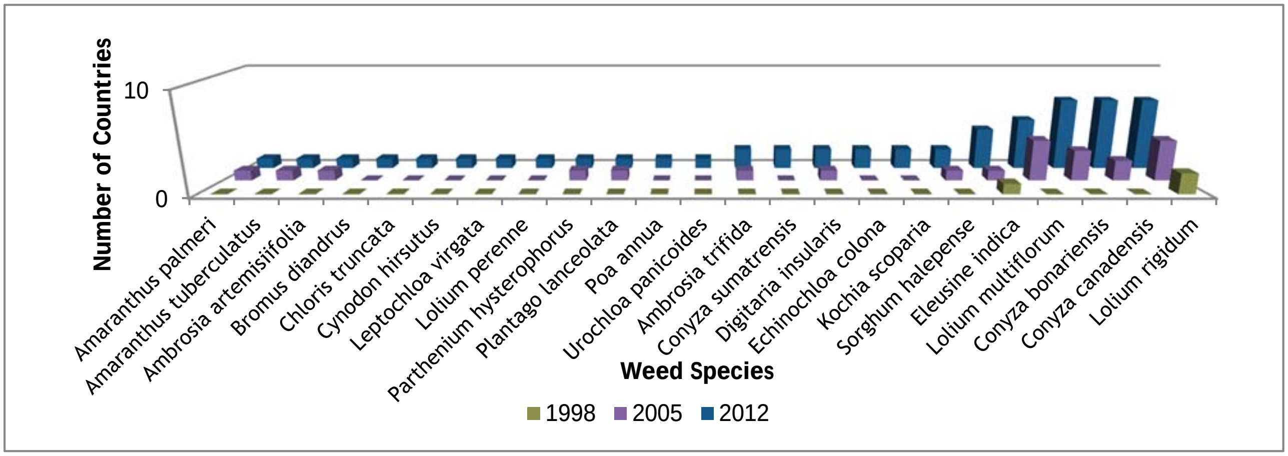
<u>Glyphosate Resistant Weeds Have Increased with Glyphosate Resistant Crop Cultivation</u>

Weed Shifts

Another potential effect of glyphosate resistant variety adoption is changes in the prevalence of different weed species, which due to natural resistance or time of emergence have an advantage under glyphosate weed management. Two studies found that glyphosate application changed weed species composition in US soybean fields compared to conventional varieties.[125,126] A study by Wilson *et al* (2007) found that weed species on plots of glyphosate resistant corn (mono-cropped) and a rotation of glyphosate resistant corn, wheat and sugar beet varied compared to conventional herbicide treatments.[127]

Selection for weeds with natural glyphosate resistance may lead to increased numbers of resistant weeds on glyphosate resistant crop plots, creating a potential long-term weed management problem.[128] Cerdeira *et al* (2010) identified eight weed species in Brazilian soybeans that have natural resistance to glyphosate and concluded that these species will likely increase on glyphosate resistant soybean fields in the future.[129]

Figure 5: Number of countries reporting glyphosate resistant weed varieties from 1998-2012



Source: Heap, I. The International Survey of Herbicide Resistant Weeds. Online. Internet. June 25, 2012. Available www.weedscience.com

Evolved Resistance

Glyphosate resistant weeds may lead to reduced or eliminated benefits of glyphosate resistant crops

The adoption of glyphosate resistant crops greatly increased glyphosate use and has likely contributed to the emergence of weed species with evolved herbicide resistance.[130] According to the 2012 International Survey of Herbicide Resistant Weeds,[131] there are currently 23 weed species with evolved resistance to glyphosate in 20 different countries. *first* reported case in 1996. The increase in the number of glyphosate resistant weeds is not entirely attributable to the dissemination of glyphosate resistant crop varieties. However, it seems likely that glyphosate resistant varieties have played a role, particularly in areas where adoption was high. Of the 156 worldwide reported cases of glyphosate resistant weed varieties, eighty-eight come from the USA, where glyphosate resistant crops were quickly adopted. Duke&Powles (2009) attributed the use of glyphosate on glyphosate resistant varieties to the emergence of resistant weed varieties in the US, Brazil and Argentina, areas where glyphosate resistant crop cultivation is common, Cerdeira *et al* (2009)concluded that glyphosate resistant weeds are becoming an increasing problem for glyphosate resistant variety adopters in South America.

Figure 5 shows growth in the global number of glyphosate resistant weed species since the first reported case in 1996. The increase in the number of glyphosate resistant weeds is not entirely attributable to the dissemination of glyphosate resistant crop varieties. However, it seems likely that glyphosate resistant varieties have played a role, particularly in areas where adoption was high. Of the 156 worldwide reported cases of glyphosate resistant weed varieties, eighty-eight come from the USA,[132] where glyphosate resistant crops were quickly adopted. Duke&Powles (2009) attributed the use of glyphosate on glyphosate resistant varieties to the emergence of resistant weed varieties in the US, Brazil and Argentina, areas where glyphosate resistant crop cultivation is common,[133] Cerdeira *et al* (2009)concluded that glyphosate resistant weeds are becoming an increasing problem for glyphosate resistant variety adopters in South America.[134]

Glyphosate resistant weeds threaten the long-term effectiveness of glyphosate for weed control. Scholars predict that likely weed management responses to glyphosate resistant weeds will be increased glyphosate use,[135] increased use of other herbicides, [136] use of tillage or other alternative weed control techniques,[137] or rotating glyphosate resistant crops with traditional crops to increase weed control diversity.[138] All of these potential reactions may offset the environmental and economic benefits of glyphosate resistant crop use. Greater diversity in weed management might discourage the development of glyphosate resistance in weeds.

Best Management Practices (BMPs) for managing herbicide resistant weeds

A recent publication by the Weed Science Society of America (2012) proposed twelve practices that would improve management of herbicide resistant weeds in the United States.

1. Understand biology of weeds present
2. Use a diversified approach, focused on preventing weed seed production and reducing number of weed seeds in the soil seed bank.
3. Plant into weed-free fields and keep seeds as weed free as possible
4. Plant weed-free crop seed
5. Scout fields routinely
6. Use multiple herbicide modes of action.
7. Apply herbicides at recommended doses at recommended timings
8. Emphasize practices that utilize crop competitiveness in weed control
9. Uses mechanical and biological practices where appropriate
10. Prevent field-field movement of weed seeds
11. Manage weed seed at harvest and after harvest to prevent buildup in the seed bank
12. Prevent an influx of weeds into the fields by managing field borders

Source: Norsworthy et al. (2012). Reducing the risks of herbicide resistance: Best Management Practices and Recommendations. *Weed Sciences*. Retrieved from http://www.wssajournals.org/doi/pdf/10.1614/WS-D-11-00155.1

Gene Flow from Transgenic Crops to Wild Species May Have Environmental Consequences

Cultivation of transgenic crops might facilitate gene flow between transgenic and non-transgenic crop varieties of the same species or between transgenic crop varieties and closely related wild plant species. Gene flow could negatively affect genetic biodiversity among closely related wild populations,[139] could confer a trait that gives a wild plant a competitive advantage (e.g. resistance to insect predation),[140] or increase the invasiveness of a concurrently growing weed variety.[141]

The probability of gene flow from transgenic crops depends on a number of factors, including the proximity of closely related species[142,143] and the natural propensity of a plant to produce viable hybrids.[144] Some suggest that assessing the probability of gene flow from transgenic crops should be undertaken on local or regional basis because the probability varies greatly between crops and agricultural ecosystems.[145,146,147]

Even if gene flow occurs, it may or may not have an impact, depending on whether it increases survivorship of the non-transgenic plant species.[148] Literature on the impact of gene flow from glyphosate resistant varieties is thin. Some have argued that the ecological risk due to gene flow conferring herbicide tolerance to wild plant species is relatively low. Unlike insect or disease resistance, herbicide resistance is likely to provide a survival advantage only in areas where herbicide is applied, therefore lessening the chance of ecological changes in natural ecosystems, even if gene flow were to occur.[149,150]

Gene flow conferring glyphosate resistance to a concurrently growing weed species might create a weed management problem, however as of yet there have been few reported cases of introgression of glyphosate tolerance to weed species. In one instance, gene flow from glyphosate resistant canola (*Brassica napus)* in Canada led to conference of glyphosate resistance to related weed species of *Brassica rapa* through hybridization.[151]

A number of technical solutions might also help to minimize the probability of damage from transgenic herbicide resistant varieties due to gene flow, including using sterile varieties, not stacking the herbicide tolerance trait with traits that might confer a competitive advantage (e.g. insect resistance) and placing the resistance gene to minimize gene flow through pollen transfer (i.e. in the plastome).[152]

While cassava is clonally propagated, it also reproduces sexually and spontaneous hybridization does occur with wild relatives, indicating that gene flow might also be possible in transgenic cassava.[153]

Impacts on Biodiversity and Ecology

The adoption of glyphosate resistant crops might reduce the overall prevalence of weeds, potentially altering food chain dynamics and reducing farm level biodiversity. The literature on the biodiversity impacts of glyphosate resistant crops is inconsistent. In some cases, results indicate that adoption of glyphosate resistant crop varieties decreased some types of biodiversity, while other cases found that biodiversity increased or was unchanged.

The literature on the effect of glyphosate resistant crops on biodiversity and ecology is focused on the impact of glyphosate crops compared to conventional crops grown with modern agricultural practices. It is important to put this literature in context of the global biodiversity picture. According to a recent report by the Convention on Biodiversity (2010), global biodiversity continued to decline from 2002-2010 and habitat loss and degradation, driven by agriculture land use, was cited as the largest contributing factor to decreasing global biodiversity. Biotechnology was not cited as one of the major threats to global biodiversity. This implies that the biodiversity impact of adopting herbicide resistant crops may be small relative to the impact of increasing agricultural land use as a whole.

Biodiversity Under Herbicide Resistant Crops Regimes: The UK Farm Level Evaluations (FSEs)

From 2000-2002, the publicly funded Farm Scale Evaluations (FSE) evaluated the impact of genetically modified herbicide resistant crop cultivation (sugar beets, maize, and canola) on plant and invertebrate biodiversity. The FSEs compared biodiversity on 60 representative plots, one half of which was treated using conventional farming practice and planted with conventional seed varieties, the other half of which was treated using a broad spectrum herbicide (either glyphosate or glufosinate) and planted with herbicide resistant seed varieties. The results of the study have been widely cited in the environmental impacts literature.

Table 4 shows some of the broad biodiversity trends from the FSE's. Herbicide tolerant maize plots tended to have greater weed biomass, and higher counts of surface invertebrate species compared to conventional plots.[154,155] Herbicide resistant sugar beet and canola plots tended to have lower weed biomass, and lower counts of soil –surface invertebrates than conventional plots.[156,157] Weed seed production tended to be lower on herbicide resistant beet and canola plots compared to conventional plots, potentially leading to biodiversity reduction in the long-term as fewer weed species are able to reproduce. Weed seed production showed the opposite trend on herbicide resistant maize.[158] Detritivores, insects that feed on decaying plant matter, were more common on plots of all three herbicide resistant varieties. Farmland birds might be adversely affected by reduced food availability on herbicide resistant beet and canola plots, but might fare better on herbicide resistant maize plots, compared to plots planted with conventional varieties, due to changes in weed biomass and prevalence of insects.[159] On a broader level, differences in biodiversity were often greater across crop types than between broad-spectrum herbicide and conventional crop treatments. See Appendix B for a more detailed discussion of the FSEs and biodiversity.

Table 4 : **Results of UK Farm Scale Evaluations: Biodiversity Indicators by Crop**

Biodiversity Indicators		**Crop**		
		HR Sugar Beets	HR Canola	HR Maize
Weed Biomass		-	-	+
Weed Seed Production		-	-	+
Soil Surface Invertebrates	Herbivores	-	-	+
	Detritivores[h]	+	+	+
Pollinators		-	-	+
*(-) indicates lower biodiversity compared to conventional treatment, (+)indicates higher biodiversity				

[h] Organisms that feed on decaying plant matter.

Section 6: Arguments against the use of glyphosate and glyphosate resistant crops

Controversy over Transgenic Crops, Glyphosate, and Glyphosate Resistant Crops

> Seemingly contradictory information about glyphosate and glyphosate resistant crops is due, in part, to different comparative standards

The use of transgenic crops is controversial and numerous popular sources claim glyphosate and glyphosate resistant crops are dangerous to human health, the environment, and the security of the global food supply.[160,161] Proponents claim that glyphosate has few human health effects and that it promotes environmental conservation, while critics claim that glyphosate is highly toxic and has led to widespread environmental damage. While both sides of the controversy claim that the public is not educated about transgenic crops, this claim has been disputed by social science research in Europe that suggests the general public has more nuanced and informed views than advocates suggest.[162,163]

Some of the conflict around glyphosate resistant crops comes from different comparative frameworks. Proponents of glyphosate resistant crops have tended to focus on the benefits of glyphosate resistant crop production compared to crop production with other herbicides. Critics of herbicide resistant crops, on the other hand, tend to focus on the absolute impact of glyphosate resistant crops, or compare glyphosate resistant cropping practices to organic agriculture. For example, when recommending a ban on glyphosate resistant crops, Greenpeace chiefly objected to their link to "industrial farming" and "unsustainable farming practices", rather than citing specific evidence of harm from the technology.[164] Similarly, the Union of Concerned Scientists argued that even though glyphosate is less toxic than some replacement herbicides, continued heavy use of herbicides will not result in environmentally sound agriculture in the long term.[165]

Negative public opinion of transgenic crops extends to Africa. A small 2004 survey of urban Nigerians found 66.5% of respondents disapproved of transgenic crops generally.[166] Food aid from the United States was rejected by some African countries in 2002 due to genetic modification. While consumers in Africa may be wary of food safety, their governments were also concerned that transgenic crops would have economic implications for exporting crops to European consumers who would not accept transgenic products.[167,168] Another view contends that the transgenic food aid was a deliberate attempt to create new markets for American transgenic crops.[169] A 2011 study surveyed stakeholders of the Water Efficient Maize for Africa (WEMA) project in Kenya, Mozambique, South Africa, Tanzania and Uganda found that poor communication affects biotechnology adoption. The study highlighted the perception that transgenic crops are incompatible with traditional agricultural techniques and farmers and consumers may object ethically to genetic engineering of food.[170]

Arguments against glyphosate due to health impacts

> Critics on both sides of the controversy criticize research methodology

As discussed in Section 4 above, glyphosate has few confirmed negative human health effects. However, anti-GMO groups and other detractors claim glyphosate causes genetic damage, cancer, miscarriage and pregnancy problems, endocrine disruption, attention deficit disorder (ADD), and birth defects, and therefore use should be curtailed.[171,172,173]

A recent (2012) Monsanto funded meta-analysis reviewed previous studies on the developmental and reproductive effects of glyphosate, many of which are cited by anti-GMO activists. The analysis concluded that "the available literature shows no solid evidence linking glyphosate exposure to adverse developmental or reproductive effects at environmentally realistic exposure conditions".[174] The authors pointed out that only 11 epidemiology studies evaluated reproductive health outcomes in humans and only one of these was designed to assess glyphosate in particular. The authors found various methodological concerns in several of the studies. Guideline-compliant animal studies found no significant impacts of glyphosate at non-maternally toxic doses. The authors dismissed the adverse effects found in non-guideline-compliant studies or attributed effects to surfactants rather than glyphosate itself. While the meta-analysis refuted the claim that glyphosate was harmful to human health in realistic exposure scenarios, it did not convincingly eliminate concerns about glyphosate use or refute claims of adverse health effects due to surfactants commonly applied with glyphosate. The study points out the limited nature of available research.

Detractors have claimed that the industry-funded studies that found no negative health impacts associated with glyphosate and glyphosate resistant crops were both biased and methodologically flawed. Some critics have highlighted the scarcity of studies on human health. Others have claimed that small sample sizes in industry funded research made finding statistically significant treatment effects unlikely.[175,176,177] On two occasions, the EPA found falsification of Roundup™ studies performed by laboratories contracted by Monsanto.[178,179]

Claims of the negative impact of glyphosate and glyphosate resistant crop use on agricultural productivity

Claims of a harmful pathogen associated with glyphosate use have also received significant attention from anti-GMO groups. In 2011, a retired plant pathologist and professor from Purdue University, Don Huber, wrote a letter to the Secretary of Agriculture alleging that glyphosate use had contributed to decreasing crop productivity and livestock health problems. In the letter, Huber claimed to identify a pathogen that was associated with both field crop disease and animal reproductive failure and also associated with glyphosate use. Dr. Huber recommended that the USDA impose an immediate moratorium on deregulation of glyphosate resistant crops until the causal association between glyphosate and plant and animal diseases was scientifically ruled out.

Dr. Huber's accusations against glyphosate have not yet been substantiated. Although Dr. Huber claimed in the letter that his conclusion was based on ongoing scientific research, none of the research upon which his conclusions were based has yet been published in peer reviewed journals. The American Phytopathological Society, of which Dr. Huber is a member, wrote an open letter in the wake of the controversy distancing itself from Dr. Huber's accusations and emphasizing the need for peer reviewed research to evaluate the veracity of his claims.[180] A more complete analysis by scientists at Purdue University found that although herbicides had been found to increase plant susceptibility to disease in some cases, there was not currently enough evidence to substantiate the claim that glyphosate use had increased disease in US maize and soybean. The Purdue report also emphasized that even in cases where plant disease did increase in the presence of glyphosate, it did not necessarily have a negative impact on yields.[181]

Controversy over Business Practices of Agro companies Producing Glyphosate and Glyphosate Resistant Crops

Anti-GMO activists frequently accuse agro-companies, particularly Monsanto, of unfair business practices, corruption, lack of transparency, misleading the public, and exploiting farmers and consumers.[182,183,184, 185] Agro-companies have also been accused of being too focused on profitability, neglecting the potential health, environmental, and socio-economic impacts of their products.[186,187, 188] Critics also object to the substantial equivalence[i] standard for approving transgenic food crops.[189]

Literature Review Methodology

The literature in this review was compiled using Integrated Risk Information System (IRIS), TOXNet, WHO Working Group reports, International Agency for Research on Cancer (IARC), Google Scholar and University of Washington databases with combinations of the following search terms: Herbicide Tolerant, Herbicide Resistant, Glyphosate Resistant, Glyphosate Tolerant, Environmental Impact, Environmental Damage, Economic Impact, Economic Benefits, Biodiversity, Cassava, Maize, Soybeans, Sugar Beets, Developing Countries, Labor Constraints, Gene Flow, Weeds, Weeding, Health, Toxicity, Primextra, Atrazine, Metolachlor, Paraquat, Diuron. Sources for the controversy over glyphosate and glyphosate resistant crops were identified using Google search with combinations of the following search terms: GMO, Glyphosate, Herbicide, Resistant, Health, Controversy, Public Opinion, Africa. The methodology also included searching for sources that were identified as central works and examining relevant lists of works cited. Interviews were conducted with two toxicologists (one academic and one in industry) and one retired industry chemist.

Many researchers and publications cited are associated with the agrochemical and seed industries.

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[i] First developed by the OECD in 1993, substantial equivalence is used to assess the safety of food from genetically modified crops. If key characteristics do not deviate significantly from the conventional food, the novel food is deemed substantially equivalent.

EPAR's innovative student-faculty team model is the first University of Washington partnership to provide rigorous, applied research and analysis to the Bill and Melinda Gates Foundation. Established in 2008, the EPAR model has since been emulated by other UW Schools and programs to further support the foundation and enhance student learning.

NOTE: The findings and conclusions contained within this material are those of the authors and do not necessarily reflect positions or policies of the Bill & Melinda Gates Foundation. Please direct comments or questions about this research to Leigh Anderson and Mary Kay Gugerty, at eparx@u.washington.edu

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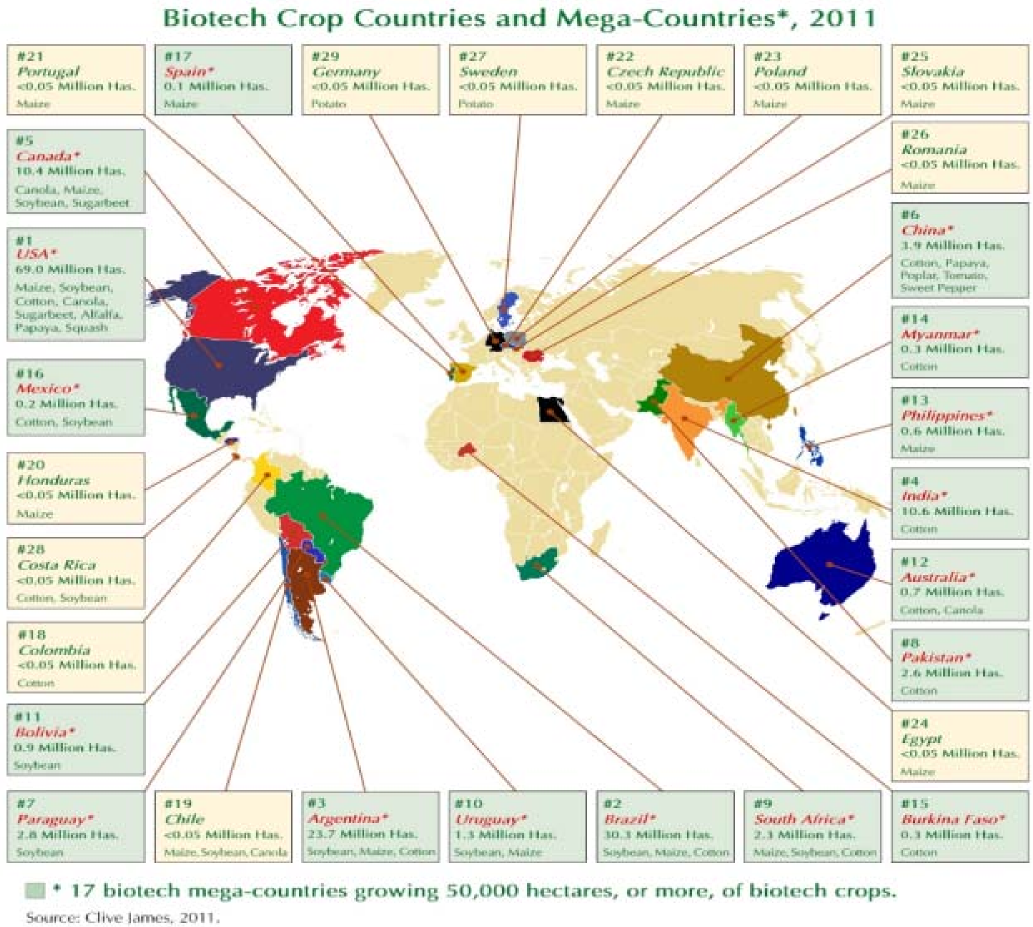
Appendix A: Map of transgenic (biotech) crops



Appendix B: Biodiversity Impact of Herbicide Resistant Crops

The following sections provide a more detailed discussion of the UK Farm Level Evaluations (FSE) on the impact of Genetically Modified Herbicide Tolerant Crops, and other literature on biodiversity impacts of herbicide tolerant crops.

Weed Biomass and Species Diversity

The results of the FSEs indicate that plant species diversity differed markedly by crop type, even before considering differences between herbicide resistant and conventional crops. For sugar beets and canola, plant densities early in the season were higher for herbicide resistant crops than for conventional crops. However, after the application of broad-spectrum herbicides, the trend was reversed, with late season plant densities lower for herbicide resistant crops. The biomass of vegetation was greater for conventional plots, likely owing to the ability of glyphosate to disproportionately target leafier weed varieties. Weed seed-rain, defined as the natural deposition of seeds on the plot, was between one third and one sixth lower on herbicide resistant plots than for conventional plots, implying that there might be decreasing plant species diversity, density and biomass in the long term. The opposite trend applied to herbicide resistant and conventional maize. Weed density was higher throughout the year and biomass after the application of herbicide was 82% higher than with conventional methods. Weed seed-rain was 87% higher using herbicide resistant. The total diversity of observed weed species was not significantly different between herbicide resistant and conventional crops for all three crop types.[190]

In a study on weed biodiversity in glyphosate resistant soybean fields in the US, Scursioni *et al* (2006) found that weed biodiversity on glyphosate resistant plots(with only one application of glyphosate applied per year) was equivalent or greater than on plots planted with conventional varieties that used conventional weed management practices(i.e. pre-emergence herbicides)[191]. However, when glyphosate was applied twice per year, weed diversity on glyphosate resistant soybean plots was roughly equivalent to plots managed with conventional weed management practices.

Invertebrates

In the FSEs, surface invertebrate species had mixed reactions to herbicide resistant and conventional treatments. Roughly half the herbicide resistant treatments produced an increase in the overall number of surface invertebrates compared to conventional crops and the other half produced a decrease. Herbicide resistant maize plots were most likely to demonstrate an increase in invertebrate numbers, while herbicide resistant beet and canola plots were most likely to show a decrease. Beetles, which often feed on weeds, were less prevalent among herbicide resistant beets and canola plots, but more prevalent in herbicide resistant maize. On the other hand, springtails (collembolan) that feed on decaying plant matter were more prevalent among all herbicide resistant crops, perhaps due to differences in herbicide application timing.[192]

Another finding of the FSE's was that the availability of weed vegetation influenced the prevalence of herbivorous invertebrate species (e.g. aphids), and the predators that feed on them (e.g. spiders). In herbicide resistant beet and canola, where weed biomass tended to be lower, there also tended to be lower counts of herbivorous invertebrates and predatory insects. In herbicide resistant maize, where weed biomass tended to be higher, there also tended to be higher counts of invertebrate herbivores and predators.[193]

Pollinators

In the FSEs, pollinators (Bees and Butterflies) were roughly ten times more prevalent in canola than in maize or beet, likely owing to greater pollen production from canola flowers. Differences in pollinator numbers between herbicide resistant and conventional crop types were inconsistent, and were not statistically significant for all time periods sampled. Herbicide resistant beet and canola pollinator counts tended to be slightly lower than for conventional crops; herbicide resistant maize pollinator counts tended to be slightly higher.[194]

Another study by Morandin & Winston(2000), comparing bee abundance in conventional, organic and glyphosate resistant canola in Alberta, Canada found that glyphosate resistant canola fields had both a lower abundance of bees than either conventional or organic fields, and also the highest pollination deficit, as measured by reductions in seeds from pollinated flowers.[195]

Farmland Birds

Some farmland bird species rely on weed seeds as a source of food. In the FSEs, the availability of weeds seeds known to be important in the diets of 17 different bird species were compared across crop types and herbicide resistant and conventional crop treatments. Availability of weed seeds for bird consumption was reduced for 16 species of birds on herbicide resistant beet plots, and significantly reduced for 10 species on herbicide resistant canola plots compared to conventional varieties. On herbicide resistant beet plots, no increases in weed seed availability for any bird species were observed, while on herbicide resistant canola plots, weed seed availability increased for only one bird species. The opposite was true of herbicide resistant maize plots, with seed availability significantly increasing for seven bird species and seed availability not being significantly reduced for any species.[196]

In another study modeling the potential effect of herbicide resistant sugar beets on the *Chenopodium Album,* a worldwide weed species that is an important source of food for farmland birds, Watkinson *et al* found that there would be a large reduction in the prevalence of this weed species under herbicide resistant sugar beet adoption, potentially greatly reducing food availability for farmland birds.[197]

Soil Microbes

The FSE's did not examine the effect of herbicide resistant crops on soil microbial activity. However there is some literature on this topic from other sources. In a study comparing soil microbial communities of ponderosa pine 9-13 years after repeated exposure to glyphosate, Busse *et al* (2001) found that although glyphosate was toxic to bacteria and fungi when grown in a soil free environment, this toxicity was not expressed when glyphosate was added to soil and soil microbial activity was independent of herbicide treatment.[198] A study by Powell *et al* (2009) in Ontario, Canada on soil food webs in glyphosate resistant maize and soybean plots found that glyphosate resistant plots sometimes showed lower counts of some biotic groups, but the effect was not consistent between samples or years.[199] The study also found that in some cases, fungal activity increased on plots planted with glyphosate resistant crops, although not on the majority of plots. Haney *et al* (2000) found that glyphosate application on Weswood silt loam soil actually stimulated microbial activity, but did not affect overall microbial biomass.[200]

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190 Heard et al 2003
191 Scursioni et al, 2006
192 Brooks et al, 2003
193 Hawes et al, 2003
194 Hawes et al, 2003
195 Morandin & Winston, 2000
196 Gibbons et al, 2003
197 Watkinson et al, 2000
198 Busse, 2001
199 Powell et al, 2009
200 Haney et al, 2000

Appendix C: Crop varieties with resistance to other herbicides

Glufosinate resistant crops are the only other commonly grown transgenic, herbicide resistant crops.[201] Transgenic crops with resistance to bromoxynil have been developed (but are no longer commercially available), and "stacked" varieties with both glyphosate and glufosinate resistance are also used.[202]

Many novel herbicide resistant crops have received regulatory approval. Table A summarizes herbicide resistant crops listed on the Center for Environmental Risk Assessment (CERA) database as regulated crops with novel traits. These crops include transgenic crops and those produced through accelerated mutagenesis or traditional plant breeding; not all crops included in the CERA database are available commercially.[203]

Table A: Crops with novel traits of herbicide resistance

Crop	Herbicide tolerance
Creeping bentgrass	Glyphosate
Sugar beet	Glyphosate, glufosinate
Canola	Glyphosate, glufosinate, bromoxynil, ioxynil,
Chicory	Glufosinate
Carnation	Sulfonylurea
Soybean	Glufosinate, imidazolinone, ALS inhibitors, glyphosate,
Cotton	ALS inhibitors, bromixynil, glyphosate, glufosinate,
Flax	ALS inhibitors
Alfalfa	Glyphosate
Tobacco	Bromoxynil, ioxynil
Rice	Glufosinate
Wheat	Glyphosate
Maize	Glufosinate, glyphosate

Source: CERA.

Targeted Mutation: A technique for engineering "non-transgenic" herbicide resistant crops

Targeted mutation,[j] a method of modifying the genetic traits of organisms without introducing new genes, and conventional breeding can be used to produce herbicide resistance. Resistance to herbicides including triazines, sulfonylureas, imidazolionones, and cyclohexanediones (sethoxdim), has been achieved through non transgenic methods.[204] Unlike glufosinate and glyphosate, these herbicides are selective and do not affect all plant species.[205]

A New York Times article from 2010 describes the potential for targeted mutation to achieve the same results as introduction of foreign genes, while avoiding the regulatory challenges associated with transgenic crops. The USDA does not currently have authority to regulate mutated crops that do not contain foreign genes. Canada is the only country that currently regulates all plants with novel traits, even those that are not transgenic.[206,207] Targeted mutation will not likely mitigate opposition from groups already opposed to transgenic crop varieties. Greenpeace, among others, is opposed to the technique because it considers it to be genetic modification.[208] Other groups object on principle to the conference of herbicide resistance to crop varieties.

[j] Also referred to as accelerated mutagenesis.

Toxicity comparison of glyphosate and herbicides for which there is potential for development of "non-transgenic" herbicide resistant cassava varieties

Glufosinate, sulfonylureas (acetolactate (ALS) inhibitors), and protoporphyrinogen IX inhibitors (protox inhibitors) have been identified as potential herbicides for non-transgenic herbicide resistant cassava. While oxadiazon (a protox inhibitor) and triasulfuron (a sulfonylurea) have acute toxicity levels comparable to glyphosate, glufosinate has a lower LD_{50} at 2000 mg/kg in rats. Oxadiazon is listed by the EPA as a likely carcinogen (See *Table B*).

Table B: Toxicity of herbicides with potential for development of non-transgenic herbicide resistant cassava

	Human Carcinogenicity*	Mammalian Toxicity(Oral)		Level of Confidence in RfD***
		Acute Toxicity**	Oral Reference Dose (RfD)***	
Glyphosate	Group E- Evidence of Non-carcinogeneticity for Humans	**Low** LD_{50} 4320mg/kg (rats)	**Increased incidence of renal tubular dilation in offspring(rats):** NOEL[a] 10 mg/kg/day Oral RfD 0.1 mg/kg/day	High
Glufosinate-ammonium	Not likely to be carcinogenic to humans	Medium LD_{50} 2000 mg/kg (rats)[209]	**Increased absolute and relative kidney weights in males (rats):** NOEL[a] 0.4 mg/kg/day Oral RfD 0.0004 mg/kg/day	Medium
Triasulfuron[k]	Group E- Evidence of Non-carcinogeneticity for Humans	Low LD_{50} >5000mg/kg (rats)[210]	**Centrilobular hepatocymegaly in males (mice):** NOEL[a] 1.2 mg/kg/day Oral RfD 0.01 mg/kg/day	High
Oxadiazon[l]	Likely To Be Carcinogenic To Humans	Low LD_{50} >3500 mg/kg (rats)	**Increased levels of serum proteins and increased liver weights (rats):** NOEL[a] 0.5 mg/kg/day Oral RfD 0.005 mg/kg/day	Medium

*Source: U.S. EPA, Office of Pesticide Programs; **Source: U.S. National Pesticide Information Center, unless otherwise footnoted; ***Source: U.S. EPA IRIS; [a] No Observable Effect Level

[201] Duke, 2009
[202] Duke, 2011
[203] Duke, 2005
[204] Duke, 2011
[205] Duke, 2005
[206] CERA website
[207] MacKenzie, 2000
[208] Voosen, 2010
[209] Bayer CropScience, 2012
[210] European Commision, 2000

[k] Triasulfuron is a sulfonylurea herbicide (acetolactate (ALS) inhibitor).
[l] Oxadiazon is a protoporphyrinogen IX inhibitor (protox inhibitor).

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