Poorer nations turn to publicly developed GM crops

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Genetically modified crops are often framed as the products of multinational corporations, but in poorer nations it is public research that is vibrant and attempting their development.

The second conference on the Cartagena Protocol on Biosafety will be held in May in Montreal, Canada[1]. One goal of the conference will be to reconcile practical challenges in implementing its articles concerning living modified organisms around the globe, particularly in developing nations. I present here the findings of a study that was a joint effort of partners from 15 developing countries on three continents and the International Food Policy Research Institute (IFPRI, Washington, DC, USA) to analyze the current state of research, regulation, genetic resources and institutional roles in developing genetically modified (GM) crops[2]. This study is meant to be representative of key trends, rather than comprehensive in approach. Information from this type of study, the first of its kind, will help scientists, policy makers and regulators understand their respective country's public GM crop research agenda, identify polices and regulatory needs for specific GM events and provide a transparent picture of national research and regulation for stakeholders. This effort in no way minimizes the need for safety evaluation, but seeks research and regulatory efficiencies and effectiveness so that all benefit.

Diversity of transformed crops and phenotypes

In the 15 countries studied (see **Box 1** for methodology), public research pipelines for GM crops contained 201 genetic transformation events for 45 different crops. (An event is defined as the stable transformation—the incorporation of foreign DNA into a living plant cell—undertaken by a single institute among the participating countries, thereby providing a unique crop-and-trait combination.) Data collection began in 2001; data were evaluated in 2002, updated and finalized through the end of 2003. These pipelines have produced GM crops, including cereals, vegetables, root, tuber and oil crops, sugar and cotton. Many are nearing or in confined trials; others

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Box 1 Research approach

Given that the development of biotech products is knowledge- and resource-intensive, the survey was directed to preselected national experts with unique expertise and knowledge of biotech, biosafety and genetic resources owing to their positions and research. These included senior research leaders in national agricultural institutes, universities and regulatory organizations, external experts, biosafety specialists and decision makers. Unlike studies that have sampled initiatives in all developing countries[22], our survey was restricted to 15 countries—those that had advanced work on GM in the regulatory stage or had regulatory procedures in place— allowing a thorough and comprehensive analysis of specific data.

The survey examined and verified peer-reviewed data collected from 15 countries and a total of 62 research institutes for 13 criteria (**Table 1**): (i) country (ii) food and fiber crops (iii) source of germ plasm (iv) gene group (v) gene (vi) phenotype category (vii) function (viii) regulatory status (ix) regulatory status by year (x) lead research institutes (xi) collaborating institutes (xii) institutional arrangement and (xiii) dissemination. This study focuses on six types of data: first, the diversity of transformed crops and phenotypes; second, the most important transgene groups; third, sources and types of genetic resources; fourth, field safety and regulatory status; fifth, research collaboration; and sixth, advancement and distribution of improved seeds. Crops were categorized and sorted following the United Nations Food and Agriculture Organization (FAO, Rome) FAOSTAT crop classification[23]. Information was collected for phenotypic trait expression, as categorized by the United States Department of Agriculture Animal and Plant Health Inspection Service (APHIS, Washington, DC, USA). The genetic resources used for transformation were analyzed to determine whether public or private institutions developed these resources, and whether their original material was local or foreign (imported). The full study[2] included data from Bulgaria, but these are not reported here because data from no other European country were available for comparison.

To study the progress of GM crops through to commercialization, data were collected by regulatory stage, emphasizing the most advanced events possible. Four stages were used: experimental (transformation events that produce stable transgenic plants derived from multiple generations at the laboratory/greenhouse/glasshouse scale); confined field trials (transformation events expressing stable traits in small-scale, single or multilocation confined trials); scale-up (transgenic plants advancing into larger, precommercial trials); or commercial release (products marketed to farmers through privately or publicly owned seed companies or other institutional mechanisms). For experimental stage entries, experts were asked to identify only highly developed biotechnologies coming from laboratory, greenhouse or glasshouse and to indicate in what stage of regulation their respective events were most accurately placed.

Table 1 Transformation events grouped by country, crops and phenotypic category

Continent	Countries	No. events[a]	Crops	Phenotypic category[b]
Africa	Egypt	17	Cotton, cucumber, maize, melons, potatoes, squash and marrow, tomatoes, watermelons, wheat	AP, FR, FR/HT, HT, HT/IR, IR, OO, PQ, VR
	Kenya	4	Cotton, maize, sweet potatoes	HT, HT/IR, OO, PQ, VR
	South Africa	20	Apples, grapes, lupin, maize, melons, pearl millet, potatoes, sorghum, soybeans, strawberry, sugar cane, tomatoes, indigenous vegetables	AP, BR, FR, HT, HT/AP, IR, PQ, VR
	Zimbabwe	5	Cotton, cowpeas, maize, sweet potatoes, tomatoes	FR, HT/VR, VR
Asia	China	30	Cabbage, chili, cotton, maize, melons, papayas, potatoes, rice, soybeans, tomatoes	AP, FR, IR, VR
	India	21	Cabbage, cauliflower, chickpeas, citrus, eggplant, mung beans, muskmelon, mustard/rapeseed, potatoes, rice, tomatoes	AP, FR, HT/AP, IR, IR/BR, OO, PQ, VR
	Indonesia	14	Cacao, cassava, chili pepper, coffee, groundnuts, maize, mung beans, papayas, potatoes, rice, shallot, soybeans, sugar cane, sweet potatoes	AP, FR, IR, PQ, VR
	Malaysia	5	Oil, palms, papayas, rice	HT, IR, VR
	Pakistan	5	Cotton, rice	HT, IR, PQ, VR
	Philippines	17	Bananas and plantains, maize, mangoes, papayas, rice, tomatoes	AP, OO, VR
	Thailand	7	Cotton, papayas, pepper, rice	AP, BR, IR, VR
Latin America	Argentina	21	Alfalfa, citrus, potatoes, soybeans, strawberry, sunflowers, wheat	AP, BR, FR, IR, IR/BR, OO, PQ, VR
	Brazil	9	Beans, maize, papayas, potatoes, soybeans	AP, BR, FR, HT, IR, PQ, VR
	Costa Rica	5	Bananas and plantains, maize, rice	AP, IR, VR
	Mexico	3	Bananas and plantains, maize, potatoes	IR, VR
Total		**201**		

[a]An event is defined as the stable transformation—incorporation of foreign DNA into a living plant cell—undertaken by a single institute among the participating countries, thereby providing a unique crop and trait combination. [b]Phenotypes are defined as follows: AP, agronomic properties; BR, bacterial resistance; FR, fungal resistance; HT, herbicide tolerance; IR, insect resistance; OO, other; PQ, product quality; VR, virus resistance.

are in later stages of field testing and seeking broader approval.

Table 1 summarizes the data by country, including total number of events, crop types transformed and phenotypic category. (Eight phenotypic categories were used: agronomic properties, bacterial resistance, fungal resistance, herbicide tolerance, insect resistance, product quality, virus resistance and other.)

The percentage of different phenotypic groups among the 201 transformation events identified is presented in **Figure 1**. Over half of the 201 transformation events involve single genes that confer biotic resistance to either viral or insect stresses to the host plant. In 11 events, stacked genes (those that simultaneously confer more than one trait) are being tested for phenotypic combinations. Some countries are working on five or fewer crops, whereas others, such as China and South Africa, are working on 15 or more.

The ten crops with the largest number of transformation events are shown in **Figure 2**. Although most transformation events have focused on cereals, significant numbers of a diverse range of transgenic vegetables, fruits, roots and tubers have also been created. Significant progress has also been achieved in transforming orphan (noncereal food staples and indigenous crops, including mung beans, beans, chickpeas, cowpeas, lupin, cacao and coffee). The greatest numbers of transformation events to date are for rice, potatoes, maize and papaya. Cotton, which is used as an oil and fiber crop, is shown for comparison with food crops in **Figure 2**.

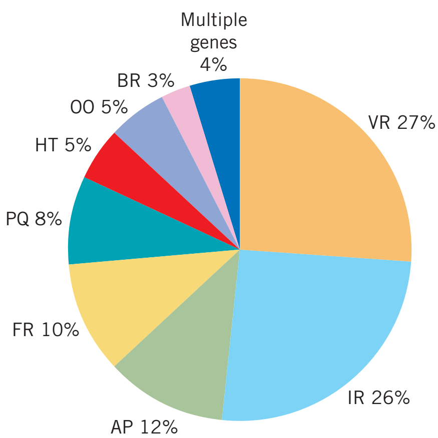

Figure 1 Total events distributed by phenotype. AP, agronomic properties; BR, bacterial resistance; FR, fungal resistance; HT, herbicide tolerance; IR, insect resistance; OO, Other; PQ,

Geographical breakdown

The largest number of transformation events were generated by the seven Asian countries surveyed (109), followed by the four African countries (54), and the four Latin American countries (38). However, Brazil also reported 37 events contracted by the private sector working with Embrapa (Brasilia), a public research institute associated with Brazil's Ministry of Agricultural (Brasilia), to address their market needs. Asian countries have products in all stages of the research pipeline, having made significant commitments to GM crops[3,4], and are already achieving significant success with insect-resistant GM cotton approvals (in China and to a lesser degree in India, and lastly, Indonesia). Despite the large number of transformation events in development in Asia, only the Philippines has approved a commercial feed crop for production, and China allows cultivation and use of publicly developed transgenic vegetables. Indonesia had approved commer-

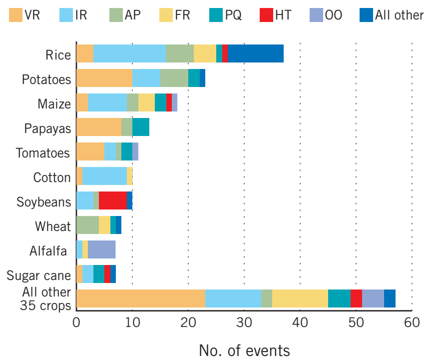

Figure 2 Phenotype characteristics sorted by number of transformation events among the top 10 crops in the study data set. AP, agronomic properties; BR, bacterial resistance; FR, fungal resistance; HT, herbicide tolerance; IR, insect resistance; OO, Other; PQ, product quality; VR, virus resistance.

cial GM cotton, but it has now been taken off the market.

Sub-Saharan Africa, with the exception of South Africa, lacks many capabilities and resources to advance such research[5]. Many countries are just considering whether to conduct research on, or to allow import of, GM crops or products. Research capacity and potential markets are evolving (e.g., for insect-resistant cotton), albeit subject to uncertainties regarding use and trade[6] . Kenya and Egypt have demonstrated competence in regulatory and import approvals, but have still not approved any crop for open testing or commercial use.

Phenotypic groupings

Table 2 presents five of the eight phenotypic groups having the highest number of clearly identified genes or gene groups. Where the specific genes were not provided, the country's description of the trait being developed is retained.

On the basis of the study data, we identified three groups of genes that appear of sufficiently robust utility and suitability for wide use. The first gene group consists of *Cry* genes from *Bacillus thuringiensis* (*Bt*) that confer resistance to lepidopteran insects. The second group consists of coat proteins of plant viruses used for inducing virus resistance. And the third consists of genes conferring herbicide tolerance. Most other gene groups and their associated phenotypic traits have not yet demonstrated robust applicability in the field. For example, no gene group has yet to confer effective fungal resistance, although much experimental activity has been spent on investigating the glucanases and chitinases.

Similarly, no group of genes has been shown to reliably confer bacterial resistance in the field, even though many investigators are studying the effects of antimicrobial peptides. Thus, success has been limited in developing crops with traits other than insect resistance, virus resistance and herbicide tolerance.

Among the genes and gene groups being tested, the *Cry* genes, coat protein genes and herbicide tolerance genes are most likely to move through regulation with fewer requirements, assuming already packaged data are accepted by the developing country in which tests would occur. This is because numerous safety reviews have been conducted on these genes in several countries. However, this does not rule out tests to address specific environmental or biodiversity concerns, as such results may not be transferable from one country to another.

The more unusual genes shown in **Table 2** include different types of insect-resistance genes, replicase genes, antisense genes and genes encoding antimicrobial peptides. Most countries are focusing on genes that are already available and have already been

Table 2 Genes and gene groups in five phenotypic categories

Phenotype category / Gene/gene group	Number of events[a]
Insect resistance	51
Bt	35
Galanthus nivalis agglutinin (Snowdrop lectin)	5
Pin	4
Trypsin inhibitor	2
Bt and trypsin inhibitor	2
Gall midge resistance gene *(Gm2)*	1
Alpha amylase inhibitor	1
Not disclosed	1
Viral resistance	53
Coat protein	47
Replicase	3
Coat protein and reporter genes	1
Coat protein and replicase	1
Antisense to tomato yellow leaf curl virus	1
Fungal resistance	21
Glucanase, chitinase	6
Glucanase, PGIP2	2
Chitinase and *ap24* antifungal protein	2
Chitinase	2
Blast resistance	2
Not disclosed	2
PGIP1 and PGIP2 isolated in South Africa	1
Grape resveratrol	1
Glucanase (PGIP3)	1
b32, PGIP2 and other selected antifungal genes	1
AP24, CH5b, GLN3	1
Herbicide tolerance	11
5-enolpyruvylshikimate-3-phosphate synthase (EPSPS)	2
BAR encoding phosphinothricin acetyltransferase	6
Acetohydroxyacid synthase (*AHAS*)	2
PsbA encoding D1 polypeptide of photosystem II	1
Bacterial resistance	7
Xa21-resistance (*R*) gene	5
Unspecified antibacterial	1
Unspecified antimicrobial peptides	1

[a]An event is defined as the stable transformation—incorporation of foreign DNA into a living plant cell—undertaken by a single institute among the participating countries, thereby providing a unique crop and trait combination. PGIP, polygalacturonase-inhibiting protein

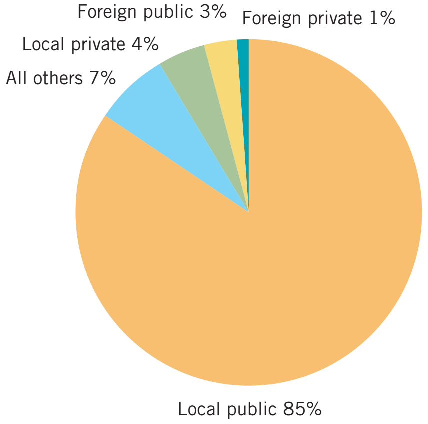

Figure 3 Source of genetic resources.

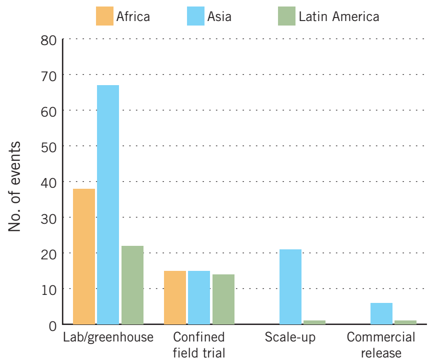

Figure 4 Number of publicly derived transformation events (in GM crops) classified by regulatory stage and region.

characterized, but a few are also investing in their own gene discovery and development, such as South Africa, Malaysia, Brazil, India and China.

Sources and types of genetic resources

Access to plant genetic resources that possess acceptable agronomic performance and are suitable for transformation is an important influence on adoption of technology. For this study, genetic resources constitute landraces, varieties and finished lines produced or derived from developing countries. Foreign resources are those brought to a developing country by an external entity. Public materials are those from any form of public institution and private materials are those from companies, as well as commodity organizations operating for and within specific developing countries.

Data from the study show that 85% of the genetic resources used for transformation have been derived locally from public materials (**Fig. 3**). Public genetic resources, defined as locally adapted and well preferred by farmers, were identified for 41 of 45 crops. Unlike private materials, these genetic resources are usually unencumbered by varietal or intellectual property claims. The use and management of this local material becomes, therefore, all the more important.

Field safety, regulatory status and costs

When study data are explained on the basis of four regulatory stages (experimental, confined trials, scale up, commercial release; see **Box 1** for explanation), a total of 127 transformation events are at the experimental stage, 44 are in confined trials, 22 in scale-up testing (mostly in China) and 7 are in the commercial-release stage (see **Fig. 4**).

Of the 44 events in confined testing, many have been under examination for years, waiting approval for scale-up or precommercial trials. Part of the difficulty with advancement, as agreed upon by study participants, is confusion about the exact amount of data required for a confined (risk management) versus open (risk assessment) trial. When possible, larger tests could be done in partnership with seed companies or with government seed production facilities to help share the regulatory costs involved (see **Box 2**).

We do not know the number of initial transformation events required to obtain the number of events in **Figure 4**. However, it is not known whether 44 events in confined testing, spread over many crops, traits and countries, will be sufficient for selecting superior GM material, to increase seed production and satisfy food safety needs. **Figure 5** shows the breakdown of these events by phenotypes, making the diversity of approaches very clear. Implications of the numbers and phenotypes finishing confined testing need further analysis, as confirmation is possible following on the 2004 harvests and test results.

Research collaborations

Study participants collected information on the type of collaboration developed (if any) and plans for dissemination of research outputs. Questions included the number of institutions involved, the type of collaboration developed and whether any plans exist for dissemination of the GM seed or planting material. Some research institutes sought partnerships to complete development of GM research products and to move research through regulation and onto public or private producers. Despite expectations of benefits to the public sector, few partnerships were developed, including those with the private sector[7].

On the basis of the data, partnerships appear to be less common events (80 transformation events, representing only 40% of the total).

Box 2 Investing in development rather than research alone

To date, most investment in biotech has been made for research infrastructure, collaboration and scientific capacity building without forseeing the need to provide for meeting regulatory requirements, especially as biosafety funds would then be diverted from research[4]. Study participants discussed the costs and regulatory requirements for developing GM products with a view to establishing efficiencies, sharing information and material so that public institutes can better comply with regulatory requirements and better manage their costs.

At the Next Harvest conference held in The Hague, Netherlands, 2002, Maria Jose Sampaio, Intellectual Property Secretariat for Embrapa, presented data from Brazil on the cost of compliance for the regulatory approval of a single transformation event, including initial greenhouse and field screening, field testing for environmental impact and food safety. The cost of compliance per event varied from $700,000 in virus-resistant papaya, to $4 million for herbicide-resistant soybeans. The higher cost per event for herbicide-resistant soybeans is mainly due to the requirement for complete animal studies[2]. Benjamin Odhiambo, plant pathologist at Kenya's Agricultural Research Institute (KARI), presented data for insect-resistant maize in Kenya. The cost for completing initial regulatory information for the maize event is $160,000, of which the major component is the cost of testing in contained structures[2]. However, these figures are now being revised.

According to Ana Sittenfeld, senior scientist, at Costa Rica's Center for Research in Cell and Molecular Biology at the Univeristy of Costa Rica (San Jose), the cost for regulatory compliance (including field trials but not technology development and molecular characterization) for virus-resistant rice in Costa Rica was $2.25 million[2]. These initial estimates are for the state of knowledge and the current biosafety regulatory system in the respective country at the time of the conference. To understand these matters more fully, a more intensive research study is required.

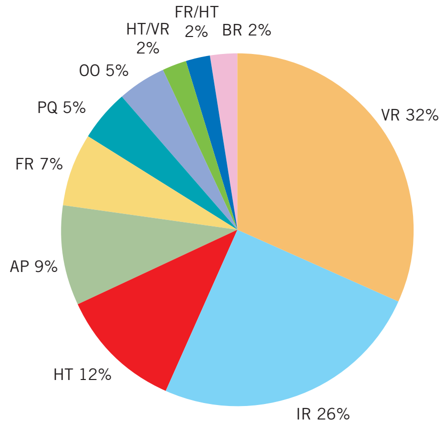

Figure 5 Phenotypic characterization of all 44 field trials. AP, agronomic properties; BR, bacterial resistance; FR, fungal resistance; HT, herbicide tolerance; IR, insect resistance; OO, Other; PQ, product quality; VR, virus resistance.

Single, public R&D institutions, working without any form of collaboration, conducted the largest proportion (60%) of research (**Table 3**). Of the 80 transformation events created through partnerships, the majority (48 events) involved public-public collaboration, most often between public research institutions in the same country.

Public-private collaborations were responsible for 21 GM crop events (10%), including a number from African countries (Egypt, Kenya and South Africa). The international private sector is involved in the majority of these cases, local seed companies playing a minor role.

Advancement and dissemination

Participating countries were asked to share preliminary plans as to how GM crops will be disseminated to farmers. Results from the study indicate that in general, such plans have not been established—44% of the scientists indicated they do not yet have suitable seed distribution mechanisms to reach farmers. Another 23% said that they would rely on public sector methods of dissemination, involving the national agricultural research institutes, or universities (**Figure 6**). Private sector partnerships were being contemplated for 7% of the cases. Preliminary plans for advancement of the remaining GM plants were not available by the end of the study.

Lack of collaborative and partnership arrangements reflect the paucity of options available for the developing countries[8]. The partnerships reported do not include time needed for acceptance, to engage farmers from early to final stages, and to meet appropriate seed or plant material suppliers.

Table 3 Partnerships sorted by institutions and by total number of transformation events created at each institution

		Institutions		Events[a]	
Continent	Country	Number	With partners	Total	With partners
Africa	Egypt	1	1	17	12
	Kenya	1	1	4	4
	Zimbabwe	4	3	5	3
	South Africa	5	2	28	7
Asia	Malaysia	2	1	5	3
	Pakistan	3	3	5	5
	Philippines	3	3	17	17
	Thailand	3	2	7	6
	Indonesia	6	2	24	5
	China	9	1	30	1
	India	14	1	21	1
Latin America	Mexico	1	0	3	0
	Brazil	2	2	9	7
	Costa Rica	3	3	5	5
	Argentina	4	3	21	4
Total		**61**	**28**	**201**	**80**

[a]An event is defined as the stable transformation—incorporation of foreign DNA into a living plant cell—undertaken by a single institute among the participating countries, thereby providing a unique crop and trait combination.

Quality of life and enhancing food security

Public research included in this study targets research that could enhance quality of life in agricultural communities and includes research on many basic food staples of importance to local economies. Some of the GM crops reported could yield several quality of life improvements (see **Table 4**):

- Reduction in the use of conventional pesticides, which has quantifiable environmental and human health benefits, as well as a reduction in application costs per acre. Of the transformation events reported in our study, 35 confer insect-resistant traits to crops, reflecting the perceived importance of pests on regional economies.
- Reduction in the use of other agrochemicals widely used to fight virus, fungus or other diseases. Eighty-four transformation events target this area, which if brought to the market successfully, should have an effect in reducing costs and increasing production.
- Improved abiotic stress crop tolerance, such as drought and salinity that place limitations on poor farmers located in less favored regions. Of the 201 events, 11 are being developed in this promising area.
- Better product quality, such as prolonged shelf life or enhanced product characteristics (foods delivering alternative carbohydrate or fat composition) that would improve transportation and consumer appeal of crops. Of 15 transformation events being developed for product qualities, 5 are in the area of nutritional enhancement and 6 are to prolong shelf life. The other 4 are for product characteristics, such as increased sucrose. There are also major public initiatives, such as HarvestPlus, that seeks to reduce micronutrient malnutrition to breed nutrient-dense staple foods (http://www.harvestplus.org).
- Alternative and more efficient provision of essential vitamins and vaccines. Nine transformation events are being developed for plant-based vaccine deployment.

Traits that increase crop yield would also be expected to have spillover effects in local economies through generation of direct and indirect employment and increase in personal income and food security. Many of the traits and genes identified have this potential, especially those for insect resistance, virus resistance, fungal resistance, herbicide tolerance, bacterial resistance and agronomic properties. However, this can be determined only in field trials, as yield reduction can occur from the introduction of genes, through either conventional or GM technologies.

Crops and traits identified in this study indicate the potential impact and importance of transgenic products to agriculture in developing countries. In addition, as we know from

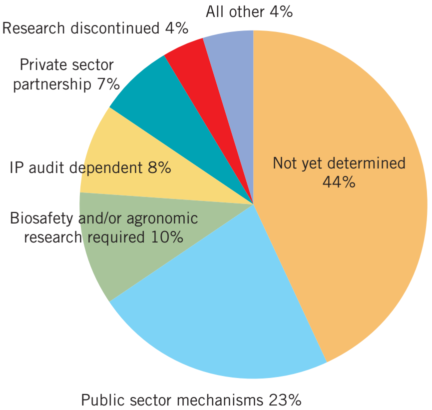

Figure 6 Projected dissemination plans for final research transformation events (in GM crops).

Table 4 Transformation events created at public research institutions related to quality-of-life categories

Trait	No. of events[a]
Insect resistance	35
Lepidoptera	35
Disease resistance	82
Bacteria	8
Fungi	21
Viruses	53
Abiotic stress tolerance	11
Drought	7
Salinity	4
Quality improvement	15
Nutritional and other	9
Enhancing shelf-life	6
Other	9
Vaccines	9
Total in this table	152
Total number of reported events	201
Percentage of all events related to quality-of-life traits	75.6%

their use in rich and developing countries, many of the GM crop events reported here have a history of food and environmental safety[9]. Approximately 76% of the events having a direct relation to quality-of-life traits, establishing their importance to agricultural development (**Table 4**).

Conclusions—getting to specifics

This study finds the public sector to be a competent, but largely unproven, player for GM crop production in developing countries. Whether national policies in these countries stimulate or deter research and technology for publicly developed GM crops is unclear; the official approval of a publicly reported transformation event for insect-resistant cotton in China appears an isolated occurrence.

All in all, this study surveyed GM crop research conducted at 61 public research institutes in 15 developing economies. These institutes have demonstrated transformation capabilities across 45 plants, within eight categories of different transgenic phenotypes, and the ability to use such genes when transforming local genetic resources.

As scientific capabilities and the number of research institutes increase, so will the diversity of crops and phenotypes. Greater attention is needed, however, for specific events where resources and knowledge are lacking to complete efficacy and safety testing. Otherwise, GM crops will remain in preliminary testing. Indeed, on the basis of this study's data, we estimate that approximately 22% of the 201 transformation events created in public research programs remain in confined testing (**Fig. 4**).

In contrast to achievements in R&D, most developing countries have only limited experience in compiling regulatory data; in fact, it has become difficult to complete all regulatory requirements. Although many research trends in this report are positive, few transformed crops have been released from confined into precommercial testing or into use.

This can be attributed to several factors: first, the overall isolation of public research institutes; second, the inability of public research to meet food safety and environmental regulatory requirements and confusion regarding regulatory standards between confined versus open trials; third, lack of regional abilities to exchange and evaluate regulatory data on specific transgenes and crops; fourth, expertise with public genetic resources but few opportunities to use or evaluate proprietary germ plasm; fifth, difficulties in planning for advancement of specific products; sixth, limited progress in determining authorities and frameworks for science-based decision making; seventh, implementing processes arising from the international level (e.g., the Cartagena Protocol for Biosafety[1,10]) as well as at the regional level (e.g., special needs confronting Africa[11]); and eight, external political barriers that either halt regulatory review (e.g., moratoriums in Thailand)[12,13] or have implications for world trade (e.g., impasse over GM crops between the United States and Europe[14,15]).

Policy, research and regulatory options are needed to expedite regulatory decisions and testing of public GM crops[15,16]. The sooner such evaluations occur, the faster GM crops unsuitable for field application can be discarded and successful GM crops moved forward, thus saving public funds and minimizing opportunity costs. This report facilitates making specific recommendations by scientists, policy makers, regulators and other stakeholders striving to evaluate and foster development of publicly derived GM plants.

Fully exploit genetic resources. Using agronomically productive genetic resources for transformation, and not just for ease of regeneration, will expedite public research. This study reveals that access to proprietary genetic resources in developing countries is extremely limited; only 6% of all transformation events used private material.

Does the high percentage of local transformed material mean reliance or dependence on public genetic resources or a deliberate independence from protected varieties or commercial germ plasm? This question is not easy to answer, as both choices present benefits and costs, and different opportunities to the research institute. The ability to transform local, widely used public or indigenous genetic resources provides the potential for greater public and farmer acceptance. Using high-performance GM public germ plasm means that farmers will not be prevented from saving seeds, nor will they potentially be under monopoly pricing of seeds. However, some private companies have promised free rights to their genes in specific crops, such as sweet potato and the rice genome for public research.

Ensure research serves the public good. Examination of potential benefits and genetic resources will determine if local resources or adapted genes need IP protection. Benefit distribution, accounting for the success in transforming local genetic resources, can form the basis for agreements between public institutes, farmer organizations and commercial producers[18]. Agreements can establish ownership among providers of transgenes (and the cost of their research) by equalizing investments with time and innovation provided by developing countries creating combinations of genes in localized crops or genetic resources[19]. Such decisions on ownership are made carefully to ensure an equitable arrangement between poor country institutions[20] and those supplying new technologies. Our data offer many examples where further investigation into ownership would be of benefit, as abilities grow for incorporating privately developed genes into crops of local value.

Local and multinational companies could play a key role for specific local GM crops, given their experience in commercial development and regulatory information, including environmental and food safety studies. However, examples of successful public-private partnerships in plant biotech are still rare, even at international research centers[21].

Creating efficiencies and competencies. Although limited collaboration does occur between developing countries and Western companies (**Table 3**), the study reveals that developing countries did not forge a single ('South-to-South') collaboration among themselves. Contacts with other countries of economic parity would create efficiencies by sharing knowledge on specific crops, traits and regulatory dossiers. For example, by using data on genes and phenotypes under study (**Table 2**), countries could meet and assemble data and experience on specific genes and their constructs, making collected and relevant information available to their respective regulators. Scientists and regulators from developing countries can also meet to discuss specific crops, where common transformation events are occurring.

Working from either specific crops or traits, joint studies can also highlight partnership models (or the lack of them) and address needs best suited for such collaboration. The same type of consultation can occur by examining crops at a particular stage in their regulation (**Fig. 4**), their required safety information and results from efficacy and safety trials. Such knowledge is valuable when selecting transgenes, considering regulatory requirements and determining which genetic resources are available or needed.

The bottom line. Although some commercially developed GM products have a role to play, GM crops developed by public research institutes should be most relevant to local needs in poor countries. Paradoxically, because they are novel, locally developed products pose unique challenges for institutes seeking regulatory approval, and gaining approval can be one of the biggest obstacles facing public GM crops in developing nations. In contrast, commercial GM crops preapproved in Western markets are more successful in gaining approvals in developing countries.

Demand for GM products by local farmers combined with the established regulatory and production track record of Western products sets the stage for interest in using GM crops in developing nations. This implies farmers may take advantage of options to grow locally unapproved Western products, thus avoiding licensing costs and IP issues. At the same time, locally produced GM crops remain in development and do not reach the same farmers, meaning their impact is yet to be seen.

ACKNOWLEDGMENTS

The author acknowledges contributions to this paper from P. Zambrano of IFPRI, and all those participating in the initial Next Harvest study. Special thanks to the National Agricultural Biotechnology Council Meeting 16, where this data and ideas were initially presented, and for the support of Alan Wildeman. Financial and technical support from The Netherlands DGIS in The Hague, The Netherlands, the Swiss Agency for Development Cooperation (Bern) and the United Kingdom's Department for Internal Development (London).

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