
CHAPTER 5

AGRICULTURAL BIOTECHNOLOGY CASE STUDIES: CHALLENGES, ACHIEVEMENTS AND LESSONS LEARNED

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EXECUTIVE SUMMARY

This chapter summarizes the background, challenges, results and lessons learned from the 19 case studies described in the preceding chapters of this book. The coverage in terms of regions, production systems, species and underlying socio-economic conditions was extensive, as were the technical challenges faced by the smallholder farming communities at the centre of the studies, as they and their national and/or international partners sought to improve livelihoods by using biotechnology to boost productivity and market penetration and better manage natural resources.

Most of the case studies involved application of a single biotechnology in a single species. They spanned the crop (seven case studies), livestock (seven) and aquaculture/fisheries (five) sectors and, apart from one dedicated to West Africa, focused on a specific initiative within a single country. Four case studies were from India, two from China and one each from Argentina, Bangladesh, Brazil, Cameroon, Colombia, Cuba, Ghana, Nigeria, South Africa, Sri Lanka, Tanzania and Thailand. A wide range of biotechnologies was used in the case studies, including some of the oldest or “traditional” methods such as fermentation, as well as several now at the forefront of “modern” science involving highly sophisticated DNA and genetic analyses, although not including genetic modification.

In terms of results, the outputs were many, varied and valuable in terms of the scientific and technical knowledge and products that were generated and the strengthening of human and infrastructural capacities that was achieved. Collectively, these also had great potential for improving on-farm productivity, market access and livelihoods. While evidence of significant outcomes (i.e. widespread adoption or use of the products by farmers and supporting partners such as extension agents and policy-makers) was not convincing in all cases, some technologies, particularly in relation to seed crops and fish, have been adopted “big time”. In the case of livestock and vegetatively propagated crops, the rate of adoption was less spectacular but nonetheless certainly meaningful to the farming communities concerned. Plausible evidence that the biotechnologies described had economic, health or environmental impacts on the lives of producers and consumers was lacking in most cases, but clear-cut for a small number of studies.

Ten general and interrelated lessons can be drawn from the case studies to guide future agricultural research for development (AR4D) investments in biotechnologies. These include: the absolute necessity for government policies and backing from donors and intergovernmental

agencies, and of partnerships both within and outside the public sector and with the farmers themselves in the planning and implementation of projects and programmes while bearing in mind also the need to retain flexibility in order to respond appropriately to evolving circumstances; and the recognition that while investments in science and technology are critical, the successful use of biotechnologies also requires their appropriate integration with other sources of science-based and traditional knowledge.

Other lessons learned from the case studies are that AR4D involving biotechnologies need not be constrained by questions involving access to, or use of, genetic resources or issues of intellectual property rights, and that products developed through biotechnologies do not need to conform to specific biosafety and food safety regulations or standards. Finally, the studies indicated that it is essential to strengthen the planning, monitoring and evaluation of biotechnologies for agricultural development. Institutional arrangements and skills in these areas are currently weak or non-existent, and should therefore be strengthened to enable governments and donors to properly evaluate and justify the financial and other investments they allocate to agricultural biotechnologies.

INTRODUCTION

All farmers are unique. The biological, physical and economic resources that they use and the activities they pursue to produce food and other agricultural products are diverse and complex. The case studies in this book certainly illustrate the immense diversity both of the challenges and of the opportunities facing smallholder farmers in developing regions. However, on closer analysis, the fundamental problems they share – and the approaches being employed to tackle them – are often similar and cut across institutional, political and national boundaries.

For a number of reasons, this chapter does not judge which of the 19 case studies resulted in the greatest hunger reduction or economic growth (or the potential for doing so in the years ahead), although several appear to have contributed greatly. The first reason is that the biotechnology interventions described set out to change only one of the many resources (e.g. usually a crop or animal species) available within the broader farming systems in which the target smallholder beneficiaries found themselves. Most likely, therefore, their livelihoods were supported by a range of interdependent activities besides producing crops, livestock and/or fish – including through the off-farm rural economy. Their livelihoods were also inevitably influenced greatly by the wider external environment – input and output markets, institutions, policies etc.

Secondly, because of the general paucity of information provided concerning farming systems, livelihoods, coping mechanisms, household food security and the like, reaching conclusions concerning the “people impacts” of (most of) the biotechnologies described here is not possible. Nor is it possible to evaluate whether, for example, the investment priorities as described in the cases studies were really the most appropriate for helping the intended beneficiaries realize their ambitions. Clearly, however, the decisions to proceed along the lines described in the studies were based on agreements within the national agricultural research systems (NARS) themselves and supported by national and/or international funding agencies and other bodies, and need not be discussed further.

The purpose of this chapter, then, is to summarize the interventions in the light of three well-established household, national and international routes for escaping or avoiding hunger, malnutrition and poverty by promoting technology change within smallholder agricultural systems, namely: sustained productivity growth of existing production patterns; diversification of activities into higher-value horticultural, livestock and aquaculture products to exploit new or existing market opportunities and thereby increase farm incomes; and enhanced stewardship of natural resources to secure the long-term sustainability of farming enterprises.

Elements covered in this chapter include: the challenges or needs addressed; the choices made in terms of the species employed and biotechnological intervention(s) made; the results obtained in terms of outputs, outcomes and impacts; and the lessons learned. Included here are suggestions for improving the rigour with which the performance of agricultural research for development (AR4D) projects involving biotechnologies may be planned and monitored and their prospects for both funding and success improved.

THE MANY CHALLENGES

Smallholders have many hurdles to overcome when trying to increase productivity, diversify the portfolio of products for marketing and home consumption, and improve their management of the natural resources available to them for sustaining their livelihoods. Many arise from the policy and institutional environments in which they have to operate, and some of these are illustrated later. Others relate to the biophysical characteristics – the natural resources and climate – of the farming systems themselves. Often, farmers, particularly smallholders, have limited or no control over these attributes. Nevertheless, as shown by undeniable past successes, science and technology coupled with improved human capital have been powerful drivers of positive

change in the performance and evolution of smallholder systems. The case studies described in this book all set out – through biotechnologies – to reduce the impediments to productivity and provide new or better products in challenging biophysical environments.

Although confined to just 19 studies, the studies illustrate all too well the great variety of technical constraints that needed to be tackled. For example, in the crop sector, efforts were directed at six species (banana, cassava, pearl millet, plantain, rice and sweet potato), all of which are widely grown as subsistence crops by smallholder farmers and are considered so critical to food security that they are covered under the International Treaty on Plant Genetic Resources for Food and Agriculture (www.planttreaty.org/content/article-xiv). More than 20 challenges were described, including: insufficient availability, high costs and poor quality of planting material due to viruses, bacteria and fungi; susceptibility to diseases, drought, flooding and storms; and slow growth and late fruiting. All of these, alone or in combination, reduced yields.

Concerning livestock, the emphasis was on dairy cattle in peri-urban settings, and on goats and sheep which are particularly important for the livelihoods of smallholders living in some of the harshest environments. Here, the main challenges included: identifying and breeding more productive animals and tackling the many causes of low reproductive efficiency to improve milk, meat and wool off-takes, quality and marketing; conserving an endangered sheep breed; diagnosing, controlling or eradicating transboundary diseases, like peste des petits ruminants (PPR) – also known as goat plague – and pests like the tsetse fly, arguably the biggest constraint to livestock and wider agricultural development in sub-Saharan Africa; and converting pig effluent into energy, biofertilizer and biochar for improving soil health and increasing milk, crop and wood production on land provided for resettlement by smallholders.

A similar picture emerged from the case studies dealing with the fishery sector, illustrated by efforts to reduce disease loads, improve yields and counter the environmental footprint and food safety concerns arising from shrimp production; to produce catfish which were more disease-resistant, faster-growing and produced better quality meat; to improve the production and quality of carp and to reduce losses due to spoilage between harvest and consumption of caught fish.

Overall, therefore, the coverage of these case studies demonstrated a clear smallholder focus in terms of species, constraints, needs, opportunities and intended benefits.

THE BIOTECHNOLOGY RESPONSES

BIOTECHNOLOGIES USED IN THE CASE STUDIES

In 2009, as part of the build-up to the FAO international technical conference on Agricultural Biotechnologies in Developing Countries (ABDC-10), FAO organized an e-mail conference which provides a good overview of the main kinds of agricultural biotechnologies being used in developing countries. This information, and the sector-specific technical documents prepared for ABDC-10, are available in FAO (2011a) and need not be repeated here.

The biotechnologies most frequently represented in the case studies of this publication used one or a combination of two DNA-based detection methods, namely restriction fragment length analysis and the polymerase chain reaction (PCR), including various more recent innovations thereof, e.g. loop-mediated isothermal amplification (LAMP). These were employed for a wide variety of purposes and across all sectors.

In the crop arena, they were used for molecular markers, such as restriction fragment length polymorphisms (RFLPs) and simple sequence repeats (SSRs) or microsatellites, to detect and validate quantitative trait loci (QTLs) for particular traits. These were then transferred into elite parental lines using marker-assisted backcrossing (MABC) to produce downy mildew-resistant and drought-tolerant pearl millet in India, rice tolerant to submergence in India and cassava mosaic disease (CMD) resistant cassava in Nigeria. In the livestock sector, DNA markers (PCR combined with RFLP) were used in India to detect FecB and introgress this prolific gene into the more productive Deccani breed through breeding and backcrossing with the smaller Garole breed which carried the gene, and in South Africa to determine the genetic diversity within, and conserve, also with the help of embryo cryopreservation, the Namaqua Afrikaner sheep breed, which is threatened with extinction. A further application was to quickly diagnose PPR in goats using LAMP, thereby enabling veterinary authorities in Cameroon to stamp out local outbreaks and stop the spread of this fatal disease to other farms. In aquaculture also, the value of PCR-based tests was amply demonstrated in India for pathogen (mainly virus) screening and for the control of disease outbreaks in shrimp farming.

Featuring prominently among the biotechnologies used in the crop sector case studies were tissue culture and micropropagation. When combined with molecular diagnostics (and in one case specific antibodies in an enzyme-linked immunosorbent assay [ELISA]), they generated

large amounts of planting material of preferred varieties free of diseases such as frog skin disease, banana bunchy top virus and “Black Sigatoka”, for distribution to farmers. Four case studies within the crop arena employed this approach (Colombia, Ghana, Nigeria and Sri Lanka), while the study in Cuba described the production and evaluation of plantain plants in tissue culture from somatic embryos.

Reproductive biotechnologies, most notably artificial insemination (AI) using cryopreserved semen, to achieve both pregnancy and genetic improvement of cattle, goats and catfish were the focus of the three case studies from Bangladesh, Argentina and Thailand respectively, and to some extent also of the efforts to improve Deccani sheep in India. A study from China also illustrated a further avenue for achieving genetic improvement, namely by producing lines of carp from the eggs of females selected for good traits through traditional breeding, which had been inseminated with inactivated sperm – a process called gynogenesis.

Other biotechnologies were less prominent but were deployed to tackle no less important issues. For example, ionizing radiation was used to sterilize male tsetse flies (known as the sterile insect technique [SIT]) for release on Unguja Island, Zanzibar, and to induce mutations and create shorter and earlier-maturing banana plants in Sri Lanka.

Two case studies from China and Brazil employed other biotechnological approaches, inspired by the need to respond to the environmental concerns arising from intensive agricultural practices. In China, bacteria (probiotics) were identified and employed as alternatives to antibiotics for improving water quality while reducing pathogenic bacteria in shrimp farming. In Brazil, the fermentation of pig effluent was used to produce biogas and biofertilizer. This same project also subjected the effluent to pyrolysis to produce biochar – a solid fertilizer to improve soil health and crop production.

Finally, the case study from West Africa described the use of fermentation – possibly the oldest biotechnology known – to preserve fish and thereby cut food wastage while at the same time improving palatability, nutritional value and marketability. Noteworthy here is the almost complete reliance on largely uncontrolled practices at household and village levels that rely on a combination of micro-organisms from the environment and traditional knowledge and experience to process raw produce into acceptable food products.

JUSTIFICATION FOR USING BIOTECHNOLOGIES

The achievements described in these case studies are summarized in the next section, but by way of “setting the scene” it is worth considering why the biotechnologies were employed in the first place. What made these propositions attractive to the people (scientists) who researched their development and encouraged their adoption by farmers? The answers provided are certainly convincing.

DNA detection methods, for instance, offered levels of specificity and sensitivity that could not be otherwise achieved for characterizing agricultural genetic resources and identifying organisms that can enhance or stunt productivity. They could also do this faster, thereby cutting breeding time and effort, and they could diagnose diseases that spread rapidly within and between fields, herds and ponds much quicker than other ways, and thereby both protect and enhance smallholder assets.

Tissue culture and micropropagation seek to ensure that farmers have sufficient, “clean” and uniform planting materials of vegetatively propagated crops at the time they are needed. Theoretically, millions of such plants could be produced in a very short time, whereas the alternative of producing these from stem or root cuttings is slower, less reliable and vulnerable to the dissemination of pests and diseases.

Artificial insemination together with semen cryopreservation relieve smallholders of the burden of keeping live males and provide a means for farmers both to ensure that their animals are bred at the correct time in their reproductive cycles and to improve their livestock using males that have desirable characteristics. Additionally, genetic material can be stored which can improve both the planning and timeliness of inseminations in outlying areas. The techniques for controlling reproduction and selecting faster-growing and more disease-resistant aquatic species offer similar advantages.

Other benefits offered by the biotechnologies described included: the prospect of getting completely rid of disease-causing pests without having continuously to use pesticides that also kill beneficial insects; using bacteria instead of antibiotics to promote animal, human and environmental health; employing biofertilizers instead of chemicals to improve productivity while lowering environmental, human health and food safety risks; and, in the absence of “cutting-edge” science and modern equipment, to produce fishery products with a longer “shelf life”, thereby reducing wastage and improving access to products with high nutritional value.

But what do the present case studies reveal about the usefulness of the biotechnologies to smallholder farmers, the beneficiaries whose welfare is the central concern of this publication? What about the realities of developing and releasing biotechnologies into fields and ponds and pastures?

THE RESULTS: OUTPUTS, OUTCOMES AND IMPACTS

Expectations are high that biotechnology will be a key ingredient within the mix of approaches taken by countries for increasing agricultural productivity and contributing to wider food security objectives such as improved nutrition and natural resource management. Volumes have been written about how to assess the consequences of all kinds of research effort, and both the methodologies and the caveats surrounding their usefulness are many: these are not described here. For readers interested in mapping the performance of agricultural research, the website of the Consultative Group on International Agricultural Research [CGIAR] Standing Panel on Impact Assessment [SPIA] is the best source of information [<http://impact.cgiar.org/>].

However, at its heart, assessing whether programmes and projects, or technologies used within them, actually make a difference revolves around collecting, analysing and linking in a plausible manner information about both the inputs made and the outputs, outcomes and impacts delivered. Critically, it also depends on who is expected to benefit – the smallholder(s) themselves and/or the wider rural and even urban population – and in what way, whether through higher yields, saved labour, improved nutrition, greater economic returns etc.? Untangling all of this is a formidable challenge, further complicated by the often significant time lags between research outputs and their transmission to end-users and beneficiaries, and the difficulties in establishing appropriate counterfactuals to improve the rigour of attribution [what if, for example, the biotechnology had not been employed?] Nevertheless, research institutions have a responsibility to make sure that the research they undertake is geared to the development needs of their countries, and to do so they must examine its performance. Put simply, they need to ask: what worked and did not work, and why. The result is a learning process through which focus can be sharpened and performance improved, and national planners and investors can be reassured that the paths proposed from research to development are as sound as possible, in view of the risks inherent in both conducting research and having the results adopted.

Below is an attempt to help the reader draw his/her own conclusions about what has been achieved within these case studies – technically, agronomically and from a socio-economic perspective.

OUTPUTS

The case studies presented in this book describe very many tangible outputs from the research conducted: new or innovative techniques; better crop and animal genotypes, products and processes; new laboratory and plant propagation facilities, including some (in Colombia, Ghana and Sri Lanka) run by farmer and community groups; smarter ways of doing things such as marker-assisted, instead of conventional, backcross transfer of useful traits; trained scientists, technicians, farmers, extension officers, labourers and even schoolchildren.

These outputs, if adopted widely and managed appropriately, would surely have great potential for improving livelihoods. The disease-free cassava, banana, plantain and sweet potato plants, the disease-resistant and drought-tolerant pearl millet, the molecular markers and DNA diagnostics for localizing important agronomic characters and fighting diseases, the quality semen stored in the deep-freezer, the fish that grow faster and the sheep that produce more lambs in experimental stations are just some of the other outputs. All of them are great successes in terms of the traditional “deliverables” expected from research enterprises, all are clear demonstrations of grand scientific and technical endeavour, knowledge generation, structural and human capacity-building. No doubt, these successful R&D enterprises also generated other important but largely hidden results in the form of scientific publications, protocols, guidelines, presentations and briefs to scientists, extension agents, farmer groups and policy-makers, which will have led in turn to stronger or wider partnerships, new grants, etc.

OUTCOMES

Outcomes are defined here as the “adoption or use of research using biotechnology by farmers, extension agents, hatcheries, commercial companies, policy-makers and policy-implementing institutions such as ministries and regulatory bodies”.

By this definition, the case studies are not uniformly persuasive in terms of delivering outcomes to scale or significance. Notwithstanding the caveats mentioned earlier, this analysis suggests that while progress was made by all in moving from research results to uptake by farmers, and by policy-making and implementing agencies, deficiencies in the amount and/or quality of information available make objective judgement difficult, and comparative assessment

impossible. Nevertheless, some technologies were taken up “big time” or at least to an extent that was meaningful in the areas or systems of the countries concerned. For example:

- The HHB 67 Improved pearl millet hybrid developed by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and partners through MABC was released by the Indian government for cultivation in 2005 as a more downy mildew-resistant and higher-yielding replacement for HHB 67. Adoption by both the seed industry and resource-poor farmers in northwest India was massive. By 2011, its cultivation had spread to almost 900 000 ha of land in northern India. Its higher yield promoted crop diversification into cash crops such as sesame and food legumes. Other attributes include early maturity, thereby escaping early-season drought. The short duration of the new hybrid also facilitated the growing of winter season rotational crops such as mustard and chickpea, thereby doubling cropping intensity. For more details, see case study (CS) 2.2 (i.e. Chapter 2.2 of this book).
- The Swarna-Sub1 semi-dwarf rice lines were developed by the International Rice Research Institute (IRRI) and partners using SSR markers to identify a major QTL for submergence tolerance and to transfer it thereafter through MABC. They were released for commercial cultivation in India in 2009 by the Central Rice Research Institute (CRRI) in Odisha and the Narendra Dev University of Agriculture and Technology (NDUAT) in Uttar Pradesh. The state governments of Uttar Pradesh, Bihar, Odisha and West Bengal then initiated large-scale seed production and dissemination. Around 38 000 tonnes of Swarna-Sub1 seed were produced in 2011, reaching over three million farmers and covering over one million ha during the 2012 wet season. These lines are highly tolerant to submergence and lodging and both improve and stabilize yields in villages prone to flooding and areas affected by flash floods. Depending on the severity of flooding, they produce 1-3 tonnes more rice per ha than Swarna, currently the most popular variety grown in the rainfed lowlands of India. There are no yield and grain quality penalties associated with Swarna-Sub1 lines in non-flood years and they provide greater opportunities for adjusting cropping patterns. The Bill and Melinda Gates Foundation supports the project “Stress-Tolerant Rice for Africa and South Asia” (STRASA), which is helping to extend the benefits of Swarna-Sub1 both within and outside India (for more details, see CS 2.7).
- The disease-free or “clean” sweet potato plant materials produced through tissue culture and micropropagation were distributed to 14 500 smallholders in different parts of Ghana. The sweet potato varieties reduced disease pressure and produced yields of 11-15 tonnes per ha. Plantain “seedlings” (2 000) were bought by individuals, non-governmental and religious organizations for field establishment. Banana and plantain hybrid plantlets were also evaluated by 1 000 farmers in Ghana. Reported advantages included 60 percent more, and 30 percent heavier, banana hands and 10 percent thicker plantain plants; better fruit juice was also mentioned (CS 2.3).
- A community-based foundation in Bangladesh now provides production-related veterinary services, including AI, to around 3 000 smallholder dairy cattle farmers. The number of farmers joining the programme has jumped in the last three to four years. Milk production has increased between three- and almost 200-fold in the dairy-producing areas of Satkhira and Sirajgonj and by five times in the Chittagong area. Milk quality has also improved (CS 3.4).
- The best Angora goat breeders in northern Patagonia (Argentina) multiplied genetically superior animals produced using laparoscopic AI. The number of animals under the scheme increased four-

fold within three years and male kids were distributed to smallholders rearing lower quality stock. A certification scheme was introduced by the Ministry of Agriculture to promote marketing of the mohair produced. The volume of certified quality mohair increased from 4 200 kg collected from 19 smallholders in 1998, to 90 000 kg from 830 smallholders in 2006 (CS 3.3).

- The Tanzanian government approved use of the SIT against tsetse flies. Millions of sterile flies were mass-reared in a special facility and released and the tsetse fly was driven to extinction on Unguja Island in Zanzibar. The percentage of small farmers with indigenous cattle increased three-fold and those holding improved breeds increased by a factor of 12, milk production nearly tripled, and ploughing with oxen improved labour and crop productivity. Wildlife management programmes initiated after tsetse eradication increased the numbers of some rare and protected wildlife species. Arising from the success of this project, the Pan African Tsetse and Trypanosomiasis Eradication Campaign (PATTEC) was established at the African Summit of 2000 under the African Union Commission (CS 3.7).
- Interspecific catfish hybrids produced by AI in Thailand were adopted by at least 1 000 hatcheries and by a far greater number of grow-out farms. They boosted the country's annual production of walking catfish (i.e. mixed species of the genus *Clarias*) from 18 000 tonnes in 1990 to 159 000 in 2004. Among freshwater commodities in Thailand, hybrid catfish production is currently second only to Nile tilapia. Advantages of the hybrid include improved growth rate, survival rate and better quality meat (CS 4.3).
- The Jian carp, developed through a combination of crossing purple red carp with Yuanjiang carp and gynogenesis was distributed to 27 provinces, municipalities and autonomous regions in China following training of more than 5 000 farmers. About 160 000 farms use the fish and it now occupies over 50 percent of the total common carp production in the country. The yield of Jian carp is over 30 percent higher than other varieties of common carp (CS 4.4).
- Several probiotic strains, added directly to water or incorporated into feeds to improve water quality, disease prevention and growth rates, have been approved by the Ministry of Agriculture in China. More than 400 companies now produce probiotics for agriculture in China, developed through research by the private sector alone or by public-private sector partnerships. Annual probiotic use in Chinese aquaculture is currently around 2 000 tonnes, far short of demand which is reported to be 30 000 tonnes, and it is now popular in commercial production of farmed shrimp. A ban imposed by the European Union (EU) because of antibiotic residues in shrimp meat was lifted in 2004. Advantages of probiotic use include much higher growth and survival rates and yields, and better water quality (ammonia levels lowered by 60 percent and nitrate levels by almost 90 percent) (CS 4.1).
- PCR-based shrimp pathogen detection services in India are sold by a number of commercial companies and employed on-site by over 100 registered hatcheries for broodstock and postlarvae screening. They have now reached over 10 000 shrimp farmers in 150 aquaculture societies in five coastal states. Disease prevalence among enterprises run by farmer societies dropped from 80 percent to 20 percent after best management practices, including PCR-based screening, were implemented (CS 4.2).
- Of the approximately one million tonnes of fish captured annually in five West African countries, about 140 000 tonnes are processed by small-scale fermentation – a figure only slightly lower than the amounts consumed as fresh or frozen fish (CS 4.5).

Other case studies describe somewhat more modest levels of uptake or acceptance by farmers. In a number of instances, no information is provided about the number of farmers actually involved, making it impossible to gauge accurately the scale of either early or subsequent uptake. Consequently, while “successful” from the standpoint of moving the technology concerned or the breed out of the laboratory or field station into the care of smallholders, substantive scale-level outcomes remain to be demonstrated. That said, it should be emphasized that, in some cases, the work was underway for less than five years, suggesting that further significant outcomes are possible and even highly likely. In others, the efforts appear to have been ongoing for longer, which suggests the presence of serious constraints to further positive developments.

Examples of case studies falling into the broad category of “work in progress” include four of the studies dealing with tissue culture-based micropropagation of vegetatively propagated plants, although each succeeded in producing plant materials – some with well-defined useful agronomic characters:

- In the case of Cuba, the technology was transferred to six commercial bio-factories which produced 44 000 plantain plants from somatic embryos and had these evaluated positively by local farmers. Bunch weights, hand and finger numbers were greater than in plants produced from corm buds. The material was planted and evaluated on 10 farms managed by individual small-scale farmers or on larger farms managed by farmer cooperatives in four provinces (CS 2.5).
- In Colombia, technology developed by the International Center for Tropical Agriculture (CIAT) and partners for propagation of disease-free cassava was transferred to a rural tissue culture laboratory run by a women’s cooperative for local plant production (CS 2.6).
- In the case of Sri Lanka, *in vitro* micropropagation of banana was transferred from a research laboratory to a tissue culture facility based in a community service centre and over 15 000 plantlets were produced per month. Around 2 500 ha of land were converted from rice to banana cultivation and about 500 farmer families cultivated tissue culture-derived Embul banana cultivars. The plants are shorter, less susceptible to storm damage and produce fruit earlier. Mutants were obtained for earliness and dwarfness (CS 2.1).
- Through collaborative work with CIAT and the International Institute of Tropical Agriculture (IITA), CMD-resistant varieties and landraces were crossed with germplasm from Latin America and, following selection of resistant genotypes based on molecular markers, a few thousand CMD-resistant *in vitro* cultured cassava plantlets were shipped from Latin American to Africa and Asia. These included over 30 000 plantlets, representing over 700 genotypes, that were shipped to Nigeria for use in breeding programmes. As a result of this initiative, two CMD-resistant cultivars, one with a starch content of 27 percent, were released to farmers in Nigeria in 2010 and 2012 (CS 2.4).

Similarly, the case studies involving the *FecB* gene in India, to diagnose PPR in goats in Cameroon, to conserve the Namaqua Afrikaner breed and to convert swine effluent in Brazil might also be defined as “work in progress”. Like some of the crop studies, each of these is in the early stage of implementation but has produced some significant outcomes that include:

- In the Indian state of Maharashtra, rams and ewes of the Deccani breed carrying the *FecB* gene for prolificacy were introduced into 36 smallholder flocks; a number of these are now designated as multiplier flocks providing *FecB*-carrier ewes to other farmers. These sheep produced 27 to 46 percent more saleable lambs than sheep without the gene (CS 3.1).
- Controlling potentially fatal PPR outbreaks in sheep and goats on two farms in Cameroon and preventing spread of the disease to others through the rapid implementation of mass vaccination and animal movement controls (CS 3.6).
- Phenotypic and genetic characterization of three flocks of Namaqua Afrikaner sheep in South Africa, establishing a biobank with frozen embryos and, in 2011, providing surplus young rams and ewes to six farmers (CS 3.2).
- Establishment in Brazil in 2008 of a pilot/demonstration farm unit for 13 selected smallholder farmers with biodigesters, an engine that converts biogas into mechanical or electrical energy for spreading the biodigested swine effluent onto pasture, crop and forest land, and both the machinery and process for producing biochar using the biogas energy and nutrient dense effluent. Farmers were able to double milk production and increase maize and soybean productivity thanks to the soil and nutrient improvements (CS 3.5).

IMPACTS

Here, impacts are defined as “economic, environmental, health and other social benefits and costs to direct adopters of the technology and to those indirectly affected such as input and output marketing agents, labourers and consumers; included are those affected by related policy changes”.

The main point to make here is that impact assessment is about finding out whether, to what extent and how, hopefully for the better, the technology has changed the lives of adopters and wider society. Advanced methods are available for predicting and quantifying the direct and indirect economic or “production effects” of research through *ex ante* and *ex post* assessments using cost-benefit analysis approaches. However, quantifying and integrating environmental, health and other social consequences into impact assessments is both conceptually and methodologically much more difficult even at the level of an individual farm or household, let alone at a village level or on a larger scale. Computable general equilibrium models have been

employed for widening the scope of the assessments and more recent modelling approaches are now available for assessing environmental impacts (Bennett, 2011).

Concerning the linkages between agriculture, nutrition and health, the complexity of this issue and how, among other interventions, agricultural yields and productivity (the present focus of most biotechnology AR4D) can contribute more effectively to better nutrition and health outcomes, are reviewed elsewhere (World Bank, 2007). Also, by embarking recently on a research programme on agriculture for nutrition and health (A4NH) aimed at reshaping agriculture towards these ends, the CGIAR is attempting to fill important gaps in knowledge and methodology. It is already clear, however, that this will require substantial data and considerable integrative skills in economics and in the social and environmental sciences and validation for agricultural development research settings. Agreeing on methodologies appropriate for quantifying the social and environmental consequences of technology adoption is therefore very much “work in progress” at this point in time.

Against this background, the following information emerged about impacts from the case studies described in Chapters 2 to 4. Omitted from consideration are what appeared to be purely general and anecdotal statements concerning the post-adoption effects of employing the biotechnologies concerned, which in any case were invariably beneficial. Unfortunately, this is how “people benefits” were framed in the great majority of cases, sometimes even in the absence of data actually demonstrating beneficial changes in yield, disease risk, product quality and safety, marketing, employment, income or other indices following adoption. Only the studies from West Africa (CS 4.5) and Thailand (CS 4.3) described – again in general terms – any of the possible adverse consequences arising from using a biotechnology. The former noted that the quality and safety of fermented fish products may be compromised by the lack of standardization of processing methods and hygiene during processing. The latter described how millions of interspecific hybrid catfish had escaped into natural water bodies during floods, leading to backcrossing with native catfish species, which may be contributing to the reduced fitness of local species. Also, the expansion of hybrid fish culture was reported to have resulted in the release of aquaculture wastes, causing mass mortality of aquatic animals and interrupting rice flowering due to excess nitrogen.

The paucity – even the absence – of hard data should certainly not be interpreted to mean that some or all of these biotechnologies did not improve incomes, reduce malnutrition, protect the environment or stimulate local, national or international trade. Indeed, on the scales at which they were adopted, it seems unimaginable that they did not positively affect the well-being of large numbers of farmers, their families and others in the wider population. Yet, in the

absence of appropriately collected and analysed data, conclusions about the significance of any effects – positive or negative – must remain speculative. Interestingly, the same general conclusion was reached from a study of non-transgenic biotechnologies (mainly tissue culture and micropropagation) in Africa (FAO, 2009).

There were, however, some noteworthy exceptions in terms of providing plausible evidence that the biotechnologies did “work” for producers and consumers:

- In 2011 alone, the improved pearl millet hybrids released in the states of Haryana and Rajasthan are estimated to have benefitted Indian farmers to the tune of US\$13.5 million more than local landraces, and seed production increased the net income of seed producers by US\$1 314 per ha or US\$6.4 million. Hybrid seed multiplication was estimated to have provided 900 000 person days of employment, nearly half of which were for women (CS 2.2).
- In Cuba, estimates of costs and incomes associated with using plantain produced by different methods showed that plants derived from somatic embryos produced a net profit per ha of \$62 Cuban pesos over those sourced from meristem cultures and a profit of almost \$8 000 Cuba pesos per ha over those derived from corm buds (CS 2.5).
- In Ghana, a three-stage strategy, including tissue culture, was used for the multiplication of sweet potato to produce clean planting materials. Almost 15 000 farmers who adopted and distributed two new resulting varieties had output increases and ready markets for their produce, and were very likely to have realized income gains (CS 2.3).
- In Sri Lanka, about 500 farmer families were involved in tissue culture banana cultivation. Farmers who switched from rice to growing mutant and other tissue culture virus-free bananas increased their incomes up to 25-fold (CS 2.1).
- In northern Patagonia in Argentina, the amount of certified quality mohair increased substantially from 1998 to 2006 and, through reforms set in motion by the government to strengthen smallholder organization, the price obtained for a bulk export order was 40 percent greater than the price that individual producers could obtain by selling individual lots of unclassified mohair (CS 3.3).
- In Zanzibar, the average monthly income of farming households increased by 30 percent between 1999 and 2002. In the same period, the proportion of households with an income over US\$25 per month increased from 69 percent to 86 percent and the proportion with an income over US\$50 per month increased from 22 percent to 36 percent. These changes can be associated with tsetse and trypanosomosis eradication since a strong correlation was observed between household income and milk yields, milk sales, and use of manure and animal power for cultivation and transport (CS 3.7).
- In the Satkhira district of Bangladesh, AI and other services provided through a community-based initiative increased the monthly incomes of most dairy farmers by between US\$1 and US\$19 per cow (CS 3.4).
- In the State of Maharashtra in India, the annual income from each ewe carrying the prolificacy *FecB* gene was around US\$34, while for non-carrier ewes it was US\$21.5 (CS 3.1).

Case study 2.4 from Nigeria provided “theoretical” estimates of benefit by carrying out *ex ante* impact economic assessments for introducing cassava cultivars with pest- and disease-resistance, as well as quality traits produced through marker-assisted breeding. Estimates indicated that over 20 years they might be worth US\$2.9 billion or, if developed only for pest- and disease-resistance, \$US1.5 billion. While undoubtedly useful for setting priorities between competing activities for research funds, and particularly for both delineating and monitoring of impact pathways during planning and implementation of activities, such studies cannot replace impact assessment carried out *ex post*.

LESSONS LEARNED

These 19 case studies, diverse as they are in terms of technology, sector, country and problem focus, and in the time periods over which they were operational, aim to provide readers with better insights into both the “what” and “why” of agricultural development achievements in developing countries using biotechnology. They also provide an opportunity for drawing general lessons for undertaking future interventions, while steering clear of defining what constitutes “success” or “failure”. This is important to stress, because the number of factors bearing upon both the nature and the size of any result is large, and some may be negative and others positive. Also, in the present context, while all studies referred to initiatives conducted outside laboratories, a sizeable number can best be described as being still at the experimental phase. In effect, they were part and parcel of the normal R&D process, allowing national staff to learn and adapt their strategies from small- to wider-scale interventions. To define these as successes or failures would clearly not be appropriate. That said, and aside from the admirable human qualities that were evident in all the case studies – technical and organizational leadership, long-term commitment, teamwork, and risk-taking – ten key and interrelated messages emerged about achieving outputs, outcomes and impacts. We look at these below.

NATIONAL AND STATE GOVERNMENT POLICIES WERE DIRECTED AT IMPROVING THE WELL-BEING OF SMALLHOLDER FARMERS

Each of the case studies illustrated efforts – often made under very difficult circumstances – to tackle one or a combination of the types of technical constraints faced by smallholder farmers in developing countries to produce more or better quality food using their indigenous crop and animal resources. The financial resources and regulatory environments within which they operated were largely determined by national exchequers, but were also supported by a variety

of external sources. While financial resources are always tight and some perceive regulation as too restrictive, the preceding chapters of this book demonstrate commitment on the part of national and/or state governments to focus on improving the productivity of smallholder enterprises and the livelihoods of those both directly involved and indirectly influenced. Probably the best illustrations of such commitments are provided by the case studies on aquaculture from China (CS 4.1 and 4.4); by the pearl millet, rice improvement and shrimp disease control projects in India (CS 2.2, 2.7 and 4.2 respectively), all of which were robustly supported by both the central and state governments and their regulatory agencies through specific crop improvement, poverty alleviation and climate change-related programmes; by the federal and various state governments in Brazil for supporting smallholder resettlement programmes (CS 3.5); by the government and various departments in Colombia with respect to cassava improvement (CS 2.6); and by the Government of Sri Lanka and its various ministries for banana micropropagation (CS 2.1).

FINANCIAL SUPPORT FROM BILATERAL AND MULTILATERAL DONORS AND FROM INTERNATIONAL AGENCIES WERE INDISPENSABLE FOR SUPPLEMENTING NATIONAL EFFORTS

The work on pearl millet (CS 2.2) was supported by the United Kingdom's Department for International Development (DFID) while the Bill and Melinda Gates Foundation currently supports the STRASA project (CS 2.7). In Ghana, work on sweet potato varieties was supported by the International Fund for Agricultural Development (IFAD), while work on plantain and banana hybrids was supported by the International Development Research Centre (IDRC), the United States Agency for International Development (USAID), the Gatsby Charitable Foundation of the United Kingdom and World Vision Ghana (CS 2.3). The development and use of PCR for shrimp diseases (CS 4.2) was assisted by FAO and the Australian Centre for International Agricultural Research (ACIAR), the latter of which also funded work to improve Deccani sheep in India (CS 3.1). Support for micropropagation in Sri Lanka (CS 2.1), the SIT in Zanzibar (CS 3.7) and LAMP in Cameroon (CS 3.6) came from the Joint FAO/IAEA Programme in Vienna, together with a number of international and bilateral donors including the Common Fund for Commodities, IFAD, the Organization of the Petroleum Exporting Countries (OPEC) Fund for International Development, and national governments (Belgium, Canada, China, Sweden, the United Kingdom and the United States).

All the biotechnologies discussed here were discovered many decades ago, and in the interval have undergone many innovations both in industrialized and in developing regions to

improve their performance and widen their application. Although, again, specific information is not available from most case studies (the Indian pearl millet (CS 2.2) and Sri Lankan banana (CS 2.1) studies being notable exceptions), it is highly likely that all the case studies benefitted from financial support for direct or indirect scientific exchanges through workshops, courses, training fellowships etc. under the great variety of programmes associated with intergovernmental and institutional agreements.

INTERNATIONAL AND NATIONAL PARTNERSHIPS WERE VITAL FOR ACHIEVING RESULTS, PARTICULARLY FOR TRANSLATING RESEARCH OUTPUTS INTO FIELD OUTCOMES AND IMPACTS; SOME INVOLVED NEW ORGANIZATIONAL MEASURES OR STRUCTURES

These case studies provided numerous examples of partnerships both within the public sector and involving international and national collaboration, as well as partnerships between public and private sector entities. For example, all but one of the crop studies described the involvement of specific CGIAR centres, such as Bioversity International, CIAT, ICRISAT, IITA and IRRI. Notable examples of partnerships in the case studies include:

- In India, the partnerships between ICRISAT, national agricultural universities such as the Chaudhary Charan Singh Haryana Agricultural University (CCSHAU) and advanced research institutes in the United Kingdom ultimately led to the releases of pearl millet varieties, began with ground-breaking work to develop DNA markers, establish genetic linkage maps, map populations and to use MABC. ICRISAT, CCSHAU and others then performed the field trials needed for government approval. The Department of Agriculture and Cooperation, seed producers and suppliers then took on responsibility for distributing seed to farmers. This was a fine example of biotechnology at work through a “value-chain” partnership approach that involved fruitful interaction between science, technology and government policy (CS 2.2).
- Also in India, an extensive network of partnerships, involving IRRI, CRRRI, NDUAT and other stakeholders from the public and private sectors, NGOs and farmers’ organizations, were built through the STRASA project to develop and widen the benefits of submergence-tolerant rice to other countries and regions. These, together with innumerable trials conducted by research stations, were critical for obtaining the approval of state governments in India to produce seed, create demand and release improved rice lines to farming communities (CS 2.7).
- Partnerships were also established between institutes within the Chinese Academy of Fishery Sciences, the Ministry of Agriculture and both its extension and regulatory departments, sales companies, demonstration farmers and smallholder producers for developing and marketing probiotics for shrimp farming. Again, regulatory decision-making was influenced, in that China was able to start re-exporting shrimp to the European Union after the lifting of a ban originally imposed because of unacceptable levels of antibiotic residues (CS 4.1).

- The partnerships in developing, standardizing, quality assuring and using PCR tests between fisheries research institutes, private agencies, hatcheries and the Marine Products Export Development Authority (MPEDA) in India which, among others, is responsible for specifying standards for producing, processing and trade in aquaculture, influenced national policy-making with respect to tests, standards and disease control measures (e.g. quarantine procedures). These were outcomes of significant national importance (CS 4.2).
- Partnerships involving NGOs and community-based approaches were evident in several case studies, some bringing positive organizational changes and new structures. These are best exemplified by:
 - The community-based micropropagation facilities for cassava established in Colombia through partnerships between CIAT, the women's farmers group from Santa Ana (ASOPROSA), an NGO (Fundacion para la Investigacion y Desarrolla Agricola) and numerous other local partners (CS 2.6).
 - Establishment of the Community-based Dairy Veterinary Foundation (CDVF), involving the NGO called BRAC, the Bangladesh Agricultural University, farmers' associations, veterinary service providers and milk processors, to deliver production-related veterinary services to smallholder farmers in four dairy-producing areas of Bangladesh (CS 3.4).
 - The Nimbkar Agricultural Research Institute (NARI) providing smallholders with more prolific and productive sheep (CS 3.1).
 - The collaboration between the Brazilian Agricultural Research Corporation (EMBRAPA), a local cooperative (COOASGO) and a local company (Retificadoro Centro Sul) to support the Campanário Settlement (CS 3.5).
 - The linkages established between the National Institute of Agricultural Technology (INTA) and the Mohair Programme established by the Government of Argentina to strengthen collective action by goat farmers (CS 3.3).
 - The contract hatchery system and establishment of farmer societies and aquaclubs promoted by MPEDA and the Network of Aquaculture Centres in Asia-Pacific (NACA) to promote sustainable shrimp rearing and marketing in India (CS 4.2).

LONG-TERM NATIONAL INVESTMENTS IN BOTH HUMAN CAPITAL AND INFRASTRUCTURE FOR SCIENCE AND TECHNOLOGY WERE CRITICAL – BUT NOT SUFFICIENT COMPONENTS OF THE RECIPE

None of the cases detailed the financial inputs but, with the exception of those from Brazil, Cameroon and South Africa (CS 3.5, 3.6 and 3.2, respectively) and excluding knowledge and products accumulated over previous years, all entailed continuous AR4D efforts that extended over 15-40 years. This is consistent with the accumulation of steady and incremental innovations and benefits from the technologies pursued rather than from rapid and revolutionary change, although innovative products did reach beneficiary groups substantially quicker than would normally be expected through other approaches.

BIOTECHNOLOGY APPROACHES DID NOT WORK IN A VACUUM – THEY WERE INTRODUCED INTO BOTH THE RESEARCH MIX AND FARMERS’ FIELDS AND PONDS THROUGH APPROPRIATE INTEGRATION WITH OTHER SOURCES OF SCIENCE-BASED AND TRADITIONAL KNOWLEDGE

This was evident from all the case studies. For example, all results using molecular markers required sound knowledge of how to select parents, make crosses and backcrosses and then select improved plants or animals. The same applied to producing hybrid catfish or carp by gynogenesis. All these biotechnologies required a sound understanding of traditional procedures for plant, animal and fish selection and breeding. Tissue culture is a relatively straightforward technique but also requires an understanding of the “basics” – the physiology, anatomy and nutritional requirements of the plant species being propagated, as well as the skills actually to grow plants in an incubator and “harden” them in a nursery before providing them to farmers. Likewise, PCR tests for animals are useful only if the people using them know about the clinical features and epidemiology of the diseases concerned – skills and knowledge that, again, can come only from a solid education in veterinary medicine. Conventional, and particularly laparoscopic, AI also requires traditional breeding, anatomical, physiological and surgical skills. There is hardly any point in producing high-quality semen if the knowledge and skills are insufficient to select males with the appropriate genetic background, to detect whether recipient females are “in heat”, synchronize oestrus or inject semen into the uterus. Similarly, releasing sterile insects in the field needs sound knowledge of insect behaviour and habitat to determine where to lay simple traps and targets to attract wild flies and release sterile ones, all of which are helped by geographical information systems (GIS). CS 2.7 on submergence-tolerant rice is a further illustration of the critical importance of “technology targeting”, in this instance using GIS and “ground truthing” to identify areas and villages affected by floods for prioritizing activities for seed distribution according to greatest need.

In no case would any of the accomplishments described have been possible without the knowledge, skills and support of the targeted smallholder groups themselves. The case studies from Colombia, Ghana, India and Sri Lanka (CS 2.6, 2.3, 4.2 and 2.1 respectively), in particular, emphasize “farmer participatory approaches” with respect to problem identification, technology development and translation.

In short, there are no quick fixes, and no room for piecemeal approaches for agricultural biotechnologies. As demonstrated by these case studies, biotechnologies need to be

incorporated into technological mixes whose foundations lie in traditional scientific knowledge, skills and approaches, with decisions concerning both their real need and utility being determined through participation with the ultimate end beneficiaries.

THE DIFFUSION OF GENETIC RESOURCES, TECHNIQUES AND KNOW-HOW ACROSS NATIONAL AND CONTINENTAL BOUNDARIES WAS AN ESSENTIAL INGREDIENT OF MOST CASE STUDIES

Few of the case studies described the origins of the plant and animal genetic resources used, although significant transfers of germplasm took place across continents and individual countries. These were in the form of rice landraces, pure line selections and varieties (within India and more widely between Asian countries); cassava plantlets (from Colombia to Nigeria); plantain and banana plantlets (from Honduras to Cuba and Ghana); probiotic bacteria strains into China from Japan, Sweden and the United States; cattle semen in Bangladesh; and even of live animals, such as the African sharp-tooth catfish into Thailand from Vietnam and *P. vannamei* specific pathogen-free shrimp from other countries in Asia into India. In the cases of both cassava and shrimp, it was only through developments in the biotechnologies described that such transfers became possible.

No case study mentioned that arrangements regarding access to and the use of genetic resources were difficult to conclude, which suggests that the institutes and countries concerned honoured the principles of unrestricted access and prior informed consent, and made such arrangements through material transfer agreements (MTAs).

INTELLECTUAL PROPERTY ISSUES NEITHER CONSTRAINED RESEARCH FOR DEVELOPMENT NOR THE PRODUCTION OR USE OF BIOTECHNOLOGY INNOVATIONS

The issue of intellectual property rights (IPR) did not appear on the “radar screen” of any case study either as a source of hindrance or of finance to promote the biotechnologies concerned. This suggests that despite the existence of patents and other forms of intellectual (e.g. MTAs) and tangible property rights covering specific components and “tricks of the trade” in using essentially all of the biotechnologies in the studies described, the institutions concerned appeared to have “freedom to operate”. The possible reasons are many, and are outlined in Chapter 9 of FAO (2011a). In the absence of specific information (apart from CS 2.2 which

noted that the John Innes Centre waived the IPR to the RFLP markers used for downy mildew resistance in pearl millet), the case studies did not mention how the technologies concerned moved across national borders.

PRODUCTS GENERATED THROUGH BIOTECHNOLOGIES DID NOT CONFORM TO SPECIFIC BIOSAFETY AND FOOD SAFETY REGULATIONS OR STANDARDS

None of the case studies indicated that the processes and products from the biotechnologies that were developed and used required new national laws and regulations covering R&D, sanitary (human and animal) and phytosanitary (plant) measures, often referred to as “biosecurity” measures (FAO, 2007). New technical rules such as labelling appeared also not to be required. While not suggesting that national regulations (e.g. on variety release, milk or mohair quality, antibiotic residue levels etc.) played no part in determining the timeframe from product development to field, hatchery or pond release, this contrasts with the additional regulatory requirements imposed by national authorities on genetically modified organisms. Nevertheless, as the case studies on shrimp and hybrid catfish (CS 4.1, 4.2 and 4.3) illustrate well, sudden changes in water levels and quality – irrespective of the technology concerned – can dramatically increase the biosecurity risks associated with intensive aquaculture. Also, CS 4.2 warned about the possibility of introducing new pathogens and diseases through the importation of new species and the future challenges in developing biotechnological tests for diagnosing such emerging diseases. The adverse consequences of some of these hazards may be long-term.

THE “GOALPOSTS” CHANGED, REQUIRING BOTH FORESIGHT AND FLEXIBILITY

Both the dynamic and risk-prone nature of producing and marketing food arising from changes in farmer and consumer preferences or field breakdown of desirable traits is illustrated by three of the case studies, namely those dealing with drought-tolerant and disease-resistant pearl millet (CS 2.2), Deccani sheep breeding (CS 3.1) and shrimp disease diagnostics and control in aquaculture (CS 4.2). In the first of these, the HHB 67 variety had to be gradually replaced after less than 20 years by HHB 67 Improved, which had greater resistance to DM, and even the advantages of this new hybrid need to be continually secured by maintenance breeding to enhance the downy mildew resistance of its parents. In the case of the Deccani sheep, farmers changed their preference for rams of the Madgyal breed because crossbred lambs of the latter

grew much faster. In the third study, the replacement of *P. monodon* with *P. vannamei* farming occurred because of the faster growth and lower cost of production and also because of the availability of specific pathogen-free stocks of *P. vannamei*.

Smallholder farmers already face an uphill battle in increasing the productivity and sustainability of their holdings to feed their families and improve their livelihoods. In the fast-changing world of the twenty-first century, agriculture and food production take place against the backdrop of climate change, ever more competitive food and commodity markets and national and global policies. Transforming smallholder production systems into sustainable business-oriented farming will consequently require greater foresight and flexibility on the part of all stakeholders to anticipate and provide locally specific technical, institutional and policy solutions for the evolving realities of such systems.

PLANNING, MONITORING AND EVALUATION OF BIOTECHNOLOGY APPLICATIONS WERE WEAK AND ARE IN URGENT NEED OF STRENGTHENING

With the exception of those involving LAMP and the SIT (CS 3.6 and 3.7 respectively), none of the case studies provided information about costs, although these can be quite substantial in the case of technologies such as tissue culture and micropropagation, developing molecular markers, AI, cryopreservation and the SIT. In fact, as illustrated by the cases of micropropagation in Ghana (CS 2.3) and the SIT in Zanzibar (3.7), it is highly questionable whether these technologies could be sustained without generating income from product sales or without the support of outside agencies. In essentially all cases, the fruits of AR4D were provided free of charge to the farmers or countries concerned. Also, most studies provided no information concerning the benefits in terms of production, productivity or financial returns, and plausible evidence about livelihood changes was conspicuous by its scarcity. The point here is that notwithstanding the value of collecting and analysing changes in yields and/or in costs and benefits in purely economic terms, a more comprehensive or multidimensional approach that supplements such traditional indices of agricultural research performance is needed to assess the true benefits or costs of agricultural interventions at the household or village level or on a larger scale.

One example from these case studies illustrates this point: the improvement of the lives of women farmers or casual labourers by providing employment through plant tissue culture and micropropagation in Colombia and Sri Lanka (CS 2.6 and 2.1 respectively). How should this be measured to track progress in closing the gender gap – an aim which in the wider

sense is essential for increasing agricultural productivity, reducing hunger and achieving food security at household, community and even national levels (FAO, 2011b)? Tools such as the women's empowerment in agriculture index (WEAI) are now becoming available. WEAI is based on household interviews, and provides an aggregate index based on defined domains for employment and sets of indicators with binary scores for each (Alkire *et al.*, 2013).

Tools designed to capture the linkages between AR4D, nutrition and the environment are also being developed and piloted using essentially the same approach and some of these, together with their application, are highlighted on the CGIAR's SPIA web site (<http://impact.cgiar.org/about>). The point here is that there is no substitute for including careful impact assessment of biotechnology applications in food and agriculture, and one can only hope that for the sake of improving both the planning and management of future projects, countries and their institutions will now give this much higher priority than in the past.

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This book documents a unique series of 19 case studies where agricultural biotechnologies were used to serve the needs of smallholders in developing countries. They cover different regions, production systems, species and underlying socio-economic conditions in the crop (seven case studies), livestock (seven) and aquaculture/fisheries (five) sectors.

Most of the case studies involve a single crop, livestock or fish species and a single biotechnology. The biotechnologies covered include some that are considered quite traditional, such as fermentation and artificial insemination, as well as other more modern ones, such as the use of DNA-based approaches to detect pathogens.

Prepared by scientists and researchers who were directly involved in the initiatives, the authors were able to provide an insider's guide to the background, achievements, obstacles, challenges and lessons learned from each case study. The final chapter of the book summarizes the background, challenges, results and lessons learned from the 19 case studies.

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