Underutilised plant species: The role of biotechnology

Ian K Dawson and Hannah Jaenicke

Position paper No.1

The International Centre for
Underutilised Crops

Championing underutilised plant species for food, nutrition and sustainable development

The International Centre for Underutilised Crops (ICUC) is an autonomous, non-profit, scientific research and training centre. ICUC promotes the use of underutilised crops for food, medicinal and industrial products, and also for environmental protection. The Centre provides expertise and works collaboratively for tropical, sub-tropical and temperate crop development.

Our Mission

Our mission is to promote the use of underutilised plant species for the benefit of humankind and the environment.

Our Goal

Our goal is to reduce poverty and suffering through the improvement and promotion of underutilised species for food, medicines, fodder and industrial needs, and for environmental protection.

ICUC Headquarters
PO Box 2075
Colombo
Sri Lanka
Tel: +94-11-2787404
Fax: +94-11-2786854
Email: icuc-iwmi@cgiar.org

Preferred citation: Dawson, I.K. and Jaenicke, H. (2006) Underutilised Plant Species: The Role of Biotechnology. Position Paper No. 1. International Centre for Underutilised Crops, Colombo, Sri Lanka. 27 pp.

ISBN: 955-1560-00-0 ISSN: 1800-2285

Design: MCN Creative Associates. Printing: Gunaratne Offset Limited. Printed on Curtis Eco-Conservation doc-it paper made from a minimum of 75% recycled pulp with the remainder made of fully chlorine free pulp. Cover photo: Carmen Perera.

Table of contents

Summary

This document presents the position of the International Centre for Underutilised Crops (ICUC) on the relationship between underutilised plant species (UPS) and biotechnology. It is intended for a wide audience, including policy makers, funding agencies, biotechnology specialists and workers generally interested in the enhanced use of these taxa.

Rapidly developing biotechnology applications receive large amounts of investment designed to improve major crop species. Such applications could also be used to promote underutilised plant species in low-income countries in innovative and more efficient ways. However, considerable investment is required in many cases, a cost that must be weighed against the limited resources available overall for underutilised plant species promotion. In order to bring real practical benefits, it is therefore crucial to focus biotechnology applications on issues where such approaches are really relevant.

Through database searches we determined whether good examples exist of biotechnology being practically applied to enhance underutilised plant species use. We concluded that such approaches have proven relevant in some areas of activity, especially in tissue culture and micropropagation. In other areas, however, benefits remain inconclusive, with a lack of integrated thinking limiting application. An example is the limited practical deployment of results from genetic diversity characterisation studies. In some cases, it is still too early to understand how relevant biotechnology will be for the promotion of underutilised plant species, but emerging lessons from major crops, key underutilised species and other groups of plant taxa will be important.

We also address here the limitations and risks associated with applying biotechnology to underutilised plant species, highlighting technology centralisation, intellectual property protection and genetic bottlenecks as important concerns. We consider what should be done in the future to ensure that biotechnology will be better applied to underutilised plant species, and emphasise the importance of partnerships between the different stakeholders involved in promotional activities. We also stress the need for rigorously monitored case studies that determine the actual benefits realised during the deployment of biotechnology approaches.

We conclude that the involvement of the International Centre for Underutilised Crops in promoting particular biotechnology activities for underutilised plant species should depend on five key issues:

- Whether projects pay proper attention to the integration of biotechnology activities within the wider context of species promotion.
- Whether projects clearly articulate how biotechnology activities relate to the needs of the rural poor (including a description of the relationship of work to practical deployment objectives).
- Whether suitable indicators are provided for monitoring biotechnology impacts.
- Whether due consideration has been given to the role of partnerships in promotion.
- Whether proper consideration has been given to property rights.

1. Introduction

The purpose of this document is to understand, and then communicate ICUC's position on, the relationship between UPS and biotechnology. Biotechnology is a rapidly developing field that has received considerable investment for major crop species and carries potential for promoting UPS in innovative and more efficient ways. However, many biotechnology techniques require considerable investment in infrastructure, consumables, staff salaries and training. This cost must be placed within the context of the limited resources available for the promotion of UPS in low-income countries, especially in the light of reductions in recent decades in public investment in agriculture and development in such nations. It is therefore important to focus biotechnology applications on issues where approaches are really relevant to UPS, minimising misapplication of techniques that, although initially appearing useful, are likely to bring few real practical benefits.

The mission of the International Centre for Underutilised Crops is to promote the sustainable use of underutilised plant species for the benefit of humankind and the environment, with a particular focus on improving the livelihoods and health of poor farmers and their families in the tropics and subtropics.

In this paper, we first define what we mean by the terms 'UPS' and 'biotechnology'. We then address the context within which biotechnology must be understood when considering the promotion of UPS. This provides a framework within which we can then address a series of questions that relate to the link between UPS and biotechnology. In particular, we attempt to address the following points:

- Are there good examples where biotechnology has been used practically to realise the potential of UPS?
- What are the difficulties, limitations and risks associated with the application of biotechnology to UPS?
- In future, what actions will be required to better apply biotechnology to UPS?

After discussing these issues, we are able to conclude with a series of considerations which ICUC will use to judge when and how to become involved in promoting particular biotechnology activities for UPS, when these are being proposed or implemented by national partners and other stakeholders.

2. What are UPS?

In order to determine how biotechnology applications may be relevant to UPS, it is first necessary to define what the characteristics of these taxa are and why they are currently underutilised. UPS contribute to the lives of hundreds of millions of people worldwide, especially in the tropics and subtropics. The range of species covered is wide, including plants that provide edible fruits, grains, leaves, nuts, oils, roots and tubers, and/or fibres, medicines, spices, stimulants and other products. This broad coverage means that it is difficult to give a concise description of UPS characteristics, and this is reflected in the wide range of labels applied to this group of taxa (see Box 1). Bearing this proviso in mind, practitioners generally use the 'underutilised plant species' label, and related terms, to describe plants that have a range of properties, some of which can be seen positively and others that have negative implications, in relation to patterns of use.

Underutilised plant species are those with under-exploited potential for contributing to food security, health, income generation and environmental services.

It is the recognition of the potential offered by the positive characteristics of UPS (listed below), for further improvement of nutrition, health, income and the environment of poor communities in the context of continued socio-economic and environmental change (Naylor et al., 2004), that determines the recent increased interest in extending the use of these species. The negative attributes of these taxa (also listed below) can be seen as areas where intervention is needed if use is to increase and displacement by major crops is not to take place under agricultural commodity globalisation.

Positive features

These species often play a crucial 'safety net' role in poor communities for food security,

Box 1. Terms to describe 'underutilised plant species'

(modified from Capacity Building International, 2003 and Jaenicke and Höschle-Zeledon, 2006)

In the strategic framework for research and development of underutilised plant species recently developed by ICUC, GFU and a range of stakeholders, UPS are defined as 'species with under-exploited potential for contribution to food security, health (nutritional and/or medicinal), income generation and environmental services'. In addition to 'underutilised', a wide range of other terms are used to describe these species, including 'minor', 'neglected', 'local', 'traditional', 'underexploited', 'underdeveloped', 'orphan', 'lost', 'new', 'niche', 'promising' and 'alternative'. Each term suggests a certain perspective with regard to limited use, but the meaning of terms is not always clear. For example, 'new' species are new in relation to what? Are species new in terms of introduction to a new geographical area or ecosystem, or new in the sense that the plant has not previously been harvested (anywhere) as a crop? Some terms, such as 'neglected' or 'orphan', carry negative connotations. A species may not have reached its full potential, but this does not necessarily mean that it has been neglected by the local community where it is found, whom may have invested in considerable informal improvement, and for whom the species may be extremely important. The term 'underutilised' is also difficult to understand clearly, since, in a broader context, all plant species, including major crops, may be classified in this way (otherwise there would be no need for continuing improvement programmes on wheat, rice and maize). Nevertheless, the term 'underutilised' is reasonably widely understood by the research and development community as a blanket term to cover the other terms above, and it is the one we adopt here.

nutrition, health and income generation, and provide additional important cultural and environmental services. Species are often well accepted through long traditional use, which has led to the development of stable informal germplasm supply pathways for their distribution and regeneration. Long familiarity means that poor farmers hold extensive germplasm and knowledge on these species; this can empower communities and encourages self-reliance, with these taxa perhaps one of the few assets they have under their direct control.

Many species have excellent nutritional profiles, with high protein, vitamin and mineral contents that can contribute to alleviating malnutrition ('hidden hunger'); several oils have excellent processing and use characteristics (see Box 2). Often, species appear highly diverse morphologically, with a wide genetic resource base assumed to be available for harnessing in potential improvement programmes (this wide gene pool also provides opportunities for the improvement of related major crops).

Ecologically, species are generally not overly competitive (not too invasive or too resource demanding) and often fit well into particular niches in highly diverse farming ecosystems, thereby contributing to overall farm production stability. This makes farmers and their environment less sensitive to rapid external changes, such as those caused by fluctuation in market demand for individual products, or global climate alterations. In addition, some species can grow well with low inputs in marginal lands that are often difficult to place under alternative production systems; this is an important consideration as the area occupied by marginal lands increases due to environmental degradation (through drought, soil loss, increased salinity and other factors).

Negative features

The variation within these species (and their relationships to other taxa), with many only partially defined semi- or incipient domesticates, has generally been superficially characterised only (both eco-geographically and genetically). This information vacuum is exacerbated by the relatively little investment that species have received in formal research and development (scientific or market) activities. Lack of characterisation can be a particular disincentive for certain categories of species entering formal markets, for example when needing to certify the efficacy and safety of medicinal plants whose mechanism of action is not well known.

Although empowerment can result when communities rather than formal research and development organisations hold most of the information on the use of species, it also limits the ability of formal institutions to become involved in promotion. As a result, these species do not have appropriate policy frameworks to support their production and marketing. Furthermore, these species tend to be important (cultivation, sale and use) locally or regionally only (or only in restricted niches if distributed more widely). This geographic restriction is partly due to limited dissemination of knowledge and germplasm, but may also, among other factors, reflect biological limitations in crossing ecological boundaries.

Furthermore, various species are limited by one or other of a number of other inherent biological characteristics, including difficulties in harvesting, low yield, low storage capability, susceptibility to various diseases (especially when grown more widely), the presence of anti-nutritional compounds (see Box 2) and difficulties in propagation, sometimes compounded by reproductive factors such as dioecy (separate male and female plants). Propagation problems not only make distribution difficult, but also restrict manipulation in breeding programmes. Furthermore, because these species often have multiple uses, crop improvement techniques that focus on only one characteristic can be inappropriate.

In addition, because UPS are often found in highly diverse multi-species farming systems, improvement of one particular species will not necessarily provide overall increases in farm productivity because of potential interactions with other taxa; if improvement results

Box 2. Nutritional characteristics of some UPS

UPS can have both positive and negative nutritional characteristics, with some examples given below.

Positive characteristics

- UPS are often high in vitamins that poor communities can be deficient in, with vitamin C in the underutilised fruit *Malpighia glabra* (Barbados cherry) being ten times higher than in kiwi fruit, and precursors of vitamin A being higher in many underutilised leafy vegetables in sub-Saharan Africa than in better-established vegetable crops.

- *Chenopodium quinoa* (quinoa) grain has a well-balanced amino acid composition and high protein content when compared to other cereals.

- *Eleusine coracana* (finger millet) and other millets have higher contents than rice or wheat in micronutrients such as calcium and iron, vitamins like niacin, sulphur-containing amino acids and soluble fibres. In addition, they have a low glycaemic index.

- *Sesamum indicum* (sesame) oil is oxidatively stable when compared to other plant oils that have a similar composition.

- The storage roots of *Ipomoea batatas* (sweet potato) are rich in riboflavin and calcium.

Negative characteristics

- The pods and seed of *Lablab purpureus* (hyacinth bean) can be poisonous due to high concentrations of cyanogenic glycosides and can only be eaten after prolonged boiling.

- The seeds of *Sphenostylis stenocarpa* (African yam bean) contain anti-nutritional factors such as cyanogenic glycosides and trypsin inhibitors. As with hyacinth bean, cooking is required to reduce toxins to safe levels, though this also decreases the level of nutrients in seed.

in competition, net benefits may not be realised. Although cultivating low input species in marginal lands carries certain clear advantages, in the past commercial interests have tended to focus on crops that can grow in more productive areas, because larger profits have been possible (now, however, the use of marginal lands receives much more attention).

Finally, these species often depend on informal germplasm delivery pathways, which means that the capacity for change through the introduction of genetically superior material is often rather limited, since the system may already be saturated with non-improved germplasm. A complementary route of developing more formal networks for germplasm distribution can be difficult to implement and is sometimes not advisable because of limited sustainability (formal networks are both more specific [less species-diverse] and more susceptible to the withdrawal of external support).

Examples of UPS

Based on combinations of the above positive and negative features, thousands of plant taxa can be considered as underutilised. To give some concept of the range of taxa involved, a list of 30 UPS from the tropics and subtropics is shown in Table 1. The species listed here have undergone relatively little formal research compared to major crops; the last five, however, while still considered as underutilised, have received more research and development attention than the rest. Listed species should not necessarily be considered as priorities for action, since methods of prioritisation are complex, with cultural- and geographic-specific elements. Listed taxa can, however, be considered as reasonably representative of recent interest across the range of categories (by use) of UPS.

3. What is biotechnology?

Biotechnology is "any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use" (The Convention on Biological Diversity).

For those involved more generally in the promotion of UPS, it is important to have an understanding of what the term 'biotechnology' encompasses. Biotechnology concerns a range of scientific tools that, if properly focused and integrated, provides powerful methods for the sustainable development of agriculture, fisheries, forestry and a range of other industries. Incorrectly, many observers consider biotechnology to be synonymous with GM and the production of transgenics (commonly referred to as GMOs, or GM crops), a mistake that has been reinforced by the terminology used by some of the participants involved in the development of GM varieties. While biotechnology includes genetic engineering, it is, however, much wider than this (Dhlamini, 2006).

For current purposes, we consider biotechnology to cover four areas of activity related to modern DNA, molecular biology and plant reproductive approaches: (i) tissue culture and micropropagation, (ii) characterising genetic diversity, (iii) genetic maps, MAS and genomics (not considered in this document are the related disciplines of proteomics and metabolomics); and (iv) GM (see Box 3 for scope and descriptions). In recent years, there has been a significant increase in biotechnology activities for major crop species in all of the above areas, though especially in the area of genomics research. The foundation of much of this increase has been the development of technologies based on the *in vitro* amplification of DNA using thermostable DNA polymerases extracted from heat tolerant micro-organisms, in a process termed polymerase chain reaction (PCR). In most cases, biotechnology work should be seen as highly multidisciplinary, with complementary work being undertaken at the same time across a number of the above four areas of activity.

Although biotechnology activities on plants have recently increased rapidly, work is often expensive and can require considerable investment in infrastructure, consumables, staff salaries and training. Costs are context- and site-specific and are therefore difficult to indicate accurately, but infrastructure expenditure alone for a basic laboratory capable of genetic diversity studies may be USD ~ 50,000, upwards of USD 500,000 for a more fully-developed facility capable of MAS, genomics and GM research. This explains why most biotechnology work has focused on major crops and has been undertaken in high-income countries, often by private companies.

Table 1. A range of 30 tropical and subtropical UPS selected from website resources of GFU, ICUC, IPGRI, and others

The last five UPS listed have received greater overall research and development attention in their promotion than other listed taxa. Associated nucleotide citations logged by NCBI are shown (see table footnote and Section 5 for discussion).

Species	Common name	Primary (local) use	NCBI nucleotide sequence citations	
			Total nucleotide sequences	EST sequences (subset of total)
Abelmoschus manihot	Bele	Leafy vegetable	2	0
Adansonia digitata	Baobab	Fruit, leafy vegetable	9	0
Aegle marmelos	Bael	Fruit	9	0
Annona sqamosa	Sugar (custard) apple	Fruit	0	0
Artocarpus heterophyllus	Jackfruit	Fruit	6	0
Bactris gasipaes	Peach palm	Fruit	64	0
Carissa edulis	Natal plum	Fruit	0	0
Ceratonia siliqua	Carob, locust bean	Fruit	17	0
Choerospondias axillaris	Lapsi	Fruit	0	0
Coriandrum sativum	Coriander	Spice	19	0
Diospyros kaki	Japanese (sweet) persimmon	Fruit	157	17
Emblica officinalis	Indian gooseberry	Fruit	0	0
Garcinia mangostana	Mangosteen	Fruit	22	0
Irvingia gabonensis	Dika nut	Fruit, nut	8	0
Kerstingiella geocarpa	Kersting's groundnut	Legume	0	0
Lablab purpureus	Hyacinth bean	Legume, fodder	18	0
Lagenaria sphaerica	Wild calabash	Fruit, medicine	4	0
Leucaena leucocephala	Leucaena	Edible pods, fodder	37	0
Metroxylon sagu	Sago palm	Sago flour (from trunk)	13	0
Plectranthus esculentus	Livingstone (coffee) potato	Tuber	0	0
Ricinodendron heudelotii	Ndjanssang	Fruit	2	0
Smallanthus sonchifolius	Yacón	Tuber	1	0
Sphenostylis stenocarpa	African yam bean	Legume	4	0
Tamarindus indica	Tamarind	Fruit	12	0
Vitellaria paradoxa	Shea	Nut	11	0
UPS that have received greater overall research attention				
Chenopodium quinoa	Quinoa	Cereal	511	424
Eleusine coracana	Finger millet	Cereal	1773	1730
Eragrostis tef	Tef	Cereal	2880	2816
Ipomoea batatas	Sweet potato	Tuber	8314	7841
Sesamum indicum	Sesame	Oil	3422	3328

NCBI, which keeps comprehensive databases of DNA sequences (GenBank) and other information (on all organisms), can be accessed via the Entrez search and retrieval system at <http://www.ncbi.nlm.nih.gov/ gquery/gquery.fcgi>. NCBI sequence searches provide access to up-to-date information in the rapidly expanding field of DNA-based biotechnology research. Furthermore, the comprehensive nature of NCBI databases means that they provide an unusual centralised window for understanding activities on disparate UPS. Shown are the total number of sequence citations for a given species and the subset of citations taken from expression libraries (ESTs, see Section 3 for definition). It is possible that entries for some species have not been located if alternative synonyms were used when uploading sequences into NCBI. Nucleotide databases also give sequences for related taxa, for hybrids, and for organisms that a given species acts as a host for (sometimes several sequences under this category), but these are excluded from the above values. As well as searching nucleotide databases, the PubMed, PubMed Central and PopSet facilities on Entrez were reviewed to find relevant biotechnology citations for each species. Searches were undertaken on 30 and 31 May 2006.

Box 3. Biotechnologies: Scope and descriptions

For the purposes of the current discussion on UPS, we categorise biotechnology into four main areas of activity that have been used to describe work on other groups of lesser-used species (e.g. FAO, 2004, from which much of the below is a summary).

Tissue culture and micropropagation

Tissue culture provides the means to generate fertile 'haploid' plants and to overcome reproductive barriers between distantly related crop relatives through embryo rescue and *in vitro* fertilisation or plant protoplast fusions. Micropropagation describes methods of *in vitro* vegetative multiplication, including rooted cuttings, somatic embryogenesis and organogenesis. Micropropagation by microcuttings is based on either axillary or adventitious budding. In the latter case, differentiated cells, usually from superficial tissues, must undergo a de-differentiating process before new shoot formation. Production of self-sufficient individuals is dependent on the *de novo* formation of an adventitious root system. Somatic embryogenesis is a process by which embryos are created from somatic tissues (as opposed to zygotic embryos from germinal cell lines). The process derives usually from callus formation induced by applying growth regulators to juvenile plant tissues. Organogenesis is the creation of plantlets from tissues such as cotyledons. Micropropagation can be used to create large numbers of clones from individual genotypes and can greatly accelerate multiplication, particularly for species that can anyway only be regenerated vegetatively. In addition, micropropagation is a way of replicating individuals with particularly desirable characteristics, including GMOs (see below, for which micropropagation is a crucial support technique), thereby delivering maximum genetic gains. Micropropagation is also used as a method to produce disease-free planting material (e.g. allowing the elimination of viruses) and as a convenient method for *in vitro* transfer between institutions of breeding material of plants propagated vegetatively. Tissue culture also includes the use of cryopreservation (very cold temperatures) and other storage methods for the *in vitro* conservation of plant material for later use.

Characterising genetic diversity

Characterising genetic diversity includes applications that: partition variation within and between stands of a species in order to devise effective sampling and conservation strategies (*in* and *ex situ*), fingerprint individuals and populations for identification purposes, assess reproductive biology (gene flow, breeding systems), determine the relationships between taxa (systematics), detect hybridisation; and determine human impacts on plant populations. A range of molecular markers has been used to evaluate genetic diversity in a very wide range of plants, and several techniques are relatively easy to apply. Most of these markers are considered to be phenotypically neutral (not linked to specific function), which can be an advantage in population-type studies, although patterns of neutral variation do not necessarily, or even frequently, correspond with adaptive variation. Some of the most popular marker systems used have been: isozymes, sequencing (nuclear and organellar genomes), RAPDs, RFLPs (nuclear and organellar), AFLPs; and SSRs (these assess variation in DNA sequences containing repeats of [normally] two, three or four base motifs, regions that are often hypervariable; until recently, SSRs were normally characterised from genomic DNA libraries). Technique of choice depends on application and resources, but currently SSRs are often the preferred method because of high allele number at individual loci, combined with codominance and transferability. RAPD and AFLP techniques provide only dominant markers, but can be applied to previously unstudied taxa because they do not rely on DNA sequence information, and they provide information easily from a large number of loci. The use of RAPDs, however, has fallen out of favour in recent years because of reproducibility concerns (cross-study comparisons difficult). More recently, SSR use has been extended to detecting repeats in ESTs (EST-SSRs) (ESTs are sequences taken from expressed DNA; that is, that subset of genomic DNA that is transcribed to mRNA; EST-SSRs are normally located in regions 5' or 3' to translated sequences, though occasionally in coding regions). EST-SSRs have some advantages in terms of scope and functionality when compared to regular SSRs. SNPs are also used to study gene variation, again often in ESTs. Both EST-SSRs and EST-SNPs are used to identify candidate gene (a gene that may be related to a particular trait) variation in pre-screens designed to incorporate potentially useful diversity into breeding programmes (see below). In the future, EST-SSRs, EST-SNPs and

Box 3. continued

sequencing are likely to increasingly become methods of choice for diversity studies. A switch to these approaches has implications for equipment costs, because the techniques required for detection can be expensive. Slightly different but related to diversity activities, marker techniques have also been used as 'fingerprinting' methods to diagnose the presence of particular species as additives or contaminants in food and other products, and to screen plant material for the presence of diseases during germplasm multiplication.

Genetic maps, marker assisted selection (MAS) and genomics

From the 1990s, significant activity has been given to the development of molecular markers and genetic linkage maps for identifying QTLs, which represent statistical associations between markers and genes that control a proportion of the genetic and phenotypic variation of a trait (many QTL may contribute to a particular trait). By establishing an association, markers can be used to understand complex traits and for MAS in breeding programmes. When combined with more traditional breeding methods, MAS has great potential to accelerate genetic improvement, particularly for certain species that are otherwise intractable or with long generation intervals. A current trend in MAS is toward the selection of superior alleles in candidate genes (these genes may be identified by genomic approaches, see below) through association genetics. This method is different from traditional approaches that rely on defined crosses because it is applied to populations of unpedigreed individuals. Over the last decade, genomics, the ultimate goal of which is to identify all genes and their functions in an organism, has burgeoned. Genomics, by revealing gene sequence similarities and synteny (common arrangements of genes, especially across related organisms), raises the prospect of information gathered on one species benefiting work on many other, perhaps less well researched, taxa (similar sequences having related functions in different species). Genomics involves a wide range of activities, including: genome sequencing, gene discovery, gene function determination (through e.g. differential expression profiling using microarrays), comparative studies (among populations, species, genera and families, including studies of synteny, cross-identification of candidate genes, detecting diversity in candidate genes by EST-SSRs and EST-SNPs, identification of targets for genetic modification), physical mapping; and the discipline of bioinformatics. Genomics, proteomics (the study of proteins) and metabolomics (the study of metabolites) are disciplines that, among others, can be combined together into a single biotechnology meta-analysis (although proteomics and metabolomics are not considered in this document), the basis of 'systems biology' (which combines concepts from different scientific disciplines to obtain an integral understanding of complex biological systems). Sometimes, genomics is considered to also include genetic engineering activities (below), but here for ease of discussion areas of activity are kept separate.

Genetic modification (GM)

GM is the use of recombinant DNA and asexual gene transfer methods to alter the structure or expression of specific genes and traits. A GMO, or transgenic, is one that has been transformed by the insertion of one or more genes (called transgenes) from another (often unrelated) organism. Active research in this area has been ongoing since the 1980s. Transferred genes may theoretically contribute to a range of properties, including: resistance/tolerance to biotic (e.g. insect, bacterial, virus) and abiotic (e.g. salt, drought) factors, modified growth patterns, improved nutritional status (e.g. improved vitamin content, reduced levels of anti-nutritional compounds), improved yield; and better management options (e.g. introduction of herbicide resistance into crops to allow easier weed control). Insertion of genes governing these traits into a new species is a substantial undertaking, often limited by lack of knowledge on molecular control, but activities are being greatly enhanced through genomic studies (see above). In the future, GM also holds the potential for the production in plants of new pharmaceutical products, 'nutraceuticals', innovative oral vaccines and new biofuels.

4. The context for understanding the role of biotechnology in the promotion of UPS

Biotechnology needs to be fully integrated with wider multidisciplinary interventions if methods are to result in desirable outcomes for UPS.

In order for biotechnology specialists to understand how their technical applications may bring benefits and innovation to UPS enhancement, it is first necessary for them to understand more about the wider context for promoting these taxa. From some of the issues that limit current use (described in Section 2 above), it is evident that enhancement could involve a very broad spectrum of activities; possible intervention points stretch in a chain from germplasm supply and production right through to marketing and delivery to consumers. In addition to this, it is important for biotechnology specialists to understand that the promotion of UPS in the tropics and subtropics is normally characterised by a number of guiding 'philosophical' features. These include: a pro-poor focus, decentralised and open access to germplasm and information, recognition of resources as public goods and equitable sharing of benefits, gender-sensitive approaches, promotion of genetic diversity; and participatory multi-stakeholder, as well as multidisciplinary, involvement. On this basis, six key intervention areas for realising UPS potential are: improving production, better post-harvest handling and processing, developing a more amenable policy and legislative environment, better marketing, capacity building, and better documentation and dissemination of information (see Box 4 for more information).

For the promotion of a given UPS, the specific activities required in these six intervention areas depend largely on the individual characteristics of the species and the particular

Box 4. Intervention areas for the promotion of UPS

Areas for possible intervention are adapted from an interdisciplinary workshop held in 2003 on the broad aspects of UPS promotion (Capacity Building International, 2003), and from ICUC's and GFU's strategic framework for underutilised plant species research and development (Jaenicke and Höschle-Zeledon, 2006).

1. Improving production. This includes: determining and maintaining genetic diversity for sustainability of production, genetic improvement, introduction of greater adaptive capability, better germplasm production and supply systems for farmer-access; and development of better on-farm management techniques.

2. Better post-harvest handling and processing. This may involve: improved techniques for storage durability, processing to give added value; and scale-up of current processing best management practices.

3. Developing a more amenable policy and legislative environment. Required are policies that: promote the access of products to existing and new markets locally and globally, promote the planting of UPS in smallholder production systems; and better protect farmers' intellectual property rights to local knowledge on taxa.

4. Better marketing. This may involve: determination of new products through market definition, appropriate certification procedures for determining quality and origin at market entry; and promotion of appropriate public-private partnerships for market development.

5. Capacity building. This involves developing better capacity for handling UPS among researchers (international, national and local) and the enhancement of indigenous knowledge networks through community-based groups. Capacity also needs to be built for buyers, industry and non-governmental organisations.

6. Better documentation and dissemination of information. Improvements are needed in: documentation of both indigenous and scientific knowledge on UPS, demonstration and dissemination of successful case studies, information exchange among all players in promotion activities; and in providing the right kind of information that allows the integration of UPS into national and international development agendas.

context in which it is found. The informal nature of UPS use means that required interventions are often more 'diffuse' than those required for more major crops. In some cases, promotion activities may be required in all of the Box 4 intervention areas; in most cases action will be needed in more than one area; in only a few cases will activity in a single intervention area be sufficient to drive significant increases in adoption. When action is needed in a number of intervention areas, any significant impact depends on proper integration between activities: otherwise, the removal of one bottleneck will simply result in its replacement by a second. In the worst scenario, attention to one bottleneck may actually confound other promotion activities, such that the overall impact of intervention is negative.

Within the above context, where does biotechnology fit? Primarily, biotechnology activities fall under 'improving production' (point 1 in Box 4), with some lesser relevance to 'better marketing' (point 4 in Box 4, through e.g. product fingerprinting during market certification). Other (non-biotechnology) activities that are likely to be included under 'improving production' are: conventional and participatory plant breeding, the development of germplasm delivery pathways (both formal and informal); and the determination of improved crop-management techniques through agronomic observations. It is therefore important to understand that, within the 'improving production' intervention area, biotechnology actions can only ever form a subset of activities.

In the current context within which ICUC wishes to understand the role of biotechnology for UPS, it is therefore important to state a cautionary proviso. This is that biotechnology is only one of several elements available for promotion, being relevant (primarily) to only one of at least six possible intervention areas. Since activities in different intervention areas compete for attention in an overall promotion programme, careful priority setting is required; each intervention activity must be understood in the widest possible context of species use, a context that is probably wider for UPS than for major crops, if maximum impact is to be realised. Furthermore, since biotechnology is in itself a multidisciplinary area of action, careful thought needs to be given to the individual elements of any biotechnology programme; in other words, it is crucial that biotechnology actions are integrated both with each other and within wider multidisciplinary interventions.

In a situation of limited funding and the generally high cost of biotechnology, it is clear that biotechnology activities undertaken on UPS need to target significant constraints. Use should be focused on applying the unique characteristics of particular biotechnology techniques to significant new opportunities for realising potential. Where this is not possible, promotion activities may be better focused elsewhere.

5. Are there good examples where biotechnology has been used practically to realise the potential of UPS?

Potential of biotechnology for UPS improvement

Based on our understanding of the characteristics and limitations of current UPS use (Section 2 above), the types of biotechnologies that are available for promotion (Section 3 above), and the context of any interventions for promotion (Section 4 above), there is potential for biotechnology to improve the production of UPS in a number of ways. Biotechnology provides methods for characterising and monitoring variation in the genetic resources of UPS that have generally been little studied to date. As well as theoretically facilitating more efficient selection of wide genetic variation in pre-breeding programmes, allowing genetic improvement, these approaches could provide for better sampling of germplasm during the development of conservation strategies for future use (*in* and *ex situ*, including the rationalisation of collections *ex situ*). Where UPS are dioecious,

Biotechnology could improve the production of UPS in a number of ways. Current and likely future genuine practical deployment is, however, difficult to evaluate, but review of work on major crops and other groups of plant species is informative.

Limited practical deployment of some biotechnology methods to UPS has already been realised, and future application for some species could be highly significant.

biotechnology could theoretically offer particular benefits through the development of sex-specific markers (this has for example been achieved for papaya), through vegetative propagation of known sexes and through the production of both-sex plants. Potential benefits are obviously species-specific, but across the wide range of UPS under consideration, promotion could come through a combination of biotechnology applications leading to innovative approaches to:

- Increase yields (overall quantity of production, specific enhancement of desirable components).
- Reduce anti-nutritional compounds (better quality of production, lower energy costs through reduced processing to ensure palatability and taste).
- Provide more uniform production (where consistency is required by markets, e.g. medicinal plants of known uniform efficacy to obtain market certification, role for ‘fingerprinting’).
- Improve disease/pest resistance (especially to minimise losses caused by increased susceptibility under wider cultivation).
- Enhance storage capability (especially roots, tubers and fruit, longer storage with less processing).
- Improve harvesting characteristics (less labour intensive, minimise losses during collection).
- Enhance ability to grow in a range of environments (where a release of biological constraints to niche production would be beneficial).
- Enhance ability to grow in very marginal areas (e.g. very dry or saline environments).
- Improve methods of multiplication (to facilitate manipulation in breeding programmes, in screening and eliminating diseases, to enhance farmer access to germplasm).

Practical deployment of biotechnology

The above paragraph addresses the *theoretical* potential of biotechnology for UPS promotion, whereas ICUC is more concerned with current and (likely) future *practical* deployment of approaches. For a number of reasons, both current and future practical application of biotechnology to UPS is difficult to evaluate. First, the development and application of biotechnology approaches to any category of plants is in most cases recent. Practical adoption related to real production problems is therefore generally still under development; approaches that have been publicly reported are limited, even for major crops. Second, extrapolation to UPS from the cases of deployment that are available for major crops is difficult because the restricted use of UPS means, by definition, that they will never receive the same investment in biotechnology; can this more limited investment overcome any ‘threshold’ level that must be surmounted before significant benefits can be realised? Furthermore, the relative proportion of overall biotechnology investment that will be received in the future by UPS is difficult to estimate. The current situation that heavily favours major crops may change, but it is not known if this will be the case, how, when and at what speed. Third, UPS promotion is focused on low-income countries that do not in most cases have the same technical capacity as wealthier nations. Technical capacity is a key feature in biotechnology use, and it is unknown how global spread of this capacity will develop in the future, since much depends on wider economic and social development.

Application of biotechnology to major crops

Bearing in mind the difficulties in assessing current and future practical deployment to UPS, a useful point from which to begin is to consider the current role of biotechnology for major crops, where such methods sometimes dominate biological research on particular taxa. Techniques such as tissue culture have realised major benefits in the breeding and distribution of crops, including in low-income countries. However, according to a recent review commissioned by the Science Council of the CGIAR, real outcomes for primary producers and consumers in some other areas of biotechnology activity have been slow to materialise, despite the large investments made (Science Council, 2006).

In particular, outcomes based on crop improvement through MAS (see Box 3) have been slow to develop. Furthermore, GM adoption has been limited to a few crops and a few major traits. Nevertheless, very large areas of arable land are now under GM production. In 2005, GM varieties were planted in 21 countries covering a total of 90 million hectares, the vast majority being four crops: GM soybean, maize, cotton and oil seed rape, all species that although important in high-income regions are also grown in medium- or low-income countries (for further information see Box 5). Significant benefits to farmers, the environment and commercial companies were reported for GM; however, wider real net benefits are difficult to calculate and are controversial because of concerns regarding the sustainability of technologies based around a few key commercial players, limited benefit sharing and the possibilities for biodiversity loss. These and other less substantial (but publicly influential) concerns related to food safety have led to consumer resistance to GM products in many countries.

According to the CGIAR Science Council review, limited outcomes from MAS could at least partly be attributed to the recent application of biotechnology compared to the time taken for variety development, often being 10 to 20 years between initial crosses and the release of a new cultivar, even for annual crops. Ten years ago, molecular marker systems were relatively cumbersome compared to current technologies, from which more rapid outcomes can be expected. The review also indicated, however, that limited serious attention had been given to examine the processes, paths and mechanisms of delivery of biotechnology outcomes to the end-users, farmers. It also suggested that the most important bottleneck to future delivery is likely to be the lack of capacity in breeding programmes in national agricultural research systems (NARS).

Box 5. Biotechnology and major crops: the example of GM

Every year, a review of commercial crop GM activities is undertaken by ISAAA. According to the 2005 review, GM varieties were planted in 21 countries (11 of which were classed as ‘developing’), with more than 50,000 hectares cultivated in each of 14 countries: Argentina, Australia, Brazil, Canada, China, India, Mexico, Paraguay, Philippines, Romania, South Africa, Spain, Uruguay and USA. The biggest planters by area included both high- and low-income countries, being (in descending order of area planted) the USA, Argentina, Brazil, Canada and China. In total, in 2005 ~ 55 million hectares of GM crops were grown in ‘industrial’ countries (~ 90% in the USA) and ~ 35 million hectares in ‘developing’ countries. In 2005, only four major commercial GM crops were cultivated, being (in descending order of area planted) soybean, maize, cotton and oil seed rape (canola), all of which are species important in countries with a wide range of different incomes. In 2005, GM rice, squash and pumpkin were also commercially planted on a smaller scale. A range of other species is currently under field trials, including in a large number of low-income countries. ‘Golden rice’, genetically engineered to produce beta-carotene in endosperm, has been developed. To date, the dominant GM trait released commercially has been herbicide tolerance, followed by insect resistance and then combinations of both traits. The net benefits to farmers and the wider community from growing GM crops is difficult to estimate. However, in 2004 economic benefit to farmers was estimated to be USD 6.5 billion and the accumulated reduction in pesticides (herbicides and insecticides) was equivalent to a 14% decrease in associated environmental impact. GM has also realised gains through reduced tillage (reducing soil erosion and energy use). In 2005, the market value of GM crops to commercial seed providers was estimated at USD 5.25 billion.

Application of biotechnology to other plants: the example of forest trees

Considering groups of plants other than major crops, one of the most interesting studies available on the application of biotechnology is a 2004 review by FAO, which covered work over the previous decade on forest trees (Box 6). Consistent with major crops, this review indicated that biotechnology work on forest trees was a growth area between 1994 and 2004. The number of reports available on different areas of activity indicated most work in tissue culture and micropropagation, with fewest studies on GM. Most activities took place in high-income regions; interestingly, however, significant activities were undertaken in India and China, both emerging economies. South America and Africa had very limited GM studies. Biotechnology activities were recorded on more than 140 genera, but most activity occurred on only six genera; considering different categories of activity, genetic diversity work had the highest number of genera studied, GM the fewest.

The review went on to consider practical outcomes of biotechnology work for forest trees and concluded that actual cases of publicly cited commercial or practical field application

Box 6. Biotechnology and forestry: an example from FAO

In 2004, FAO undertook a review of biotechnology activities on forest trees, based on more than 2,700 references (primarily public sources, meaning that not all information held by the private sector could be accessed) from the preceding decade (FAO, 2004). By considering actual practical examples of biotechnology application, the review provided one of the best insights into the use of biotechnology on a diverse group of plant species that were not major food crops. As such, it is an illustrative example when considering the application of biotechnology to UPS. Principal observations from the review are summarised below.

Biotechnology as a growth area

Between 1999 and 2004 there was a threefold increase in forest biotechnology activity citations compared with 1994 to 1999.

Not just GM

Biotechnology work could be categorised into four main areas of activity (see Box 3), with GM being the smallest of these. The percentage of activities falling into different categories were as follows: 34% tissue culture and micropropagation (*in vitro* techniques: rooting cuttings, somatic embryogenesis, organogenesis); 26% characterising genetic diversity (with SSRs, AFLPs, etc.); 21% genetic maps, MAS and genomics; and, 19% GM. Within GM activities, 70 field trials on fruit and ornamental trees were recorded (mostly related to fungal, insect and viral resistance, several each related to altered fruit ripening and sugar alcohol levels), including 18 trials on *Carica papaya* (papaya).

Activities biased toward high-income regions

Excluding GM, biotechnology activities were recorded in 76 countries, although 71% of all activities were undertaken in high-income countries. The percentage of activities by region were as follows: 39% Europe; 24% Asia; 23% North America; 6% Oceania; 5% South America; 3% Africa; and < 1% Near East. Despite a bias toward high-income regions, it was however interesting to observe that 9% of activities were undertaken in India and 6% in China, both emerging economies. Considering GM, the USA had, by far, the greatest number of field trials (although the one country with commercial GM planting, China, is an emerging rather than high-income economy; see more below). South America and Africa had < 1% each of GM studies (in Africa, activities were restricted to South Africa).

Taxa coverage limited

Although biotechnology activities were recorded on more than 140 genera, 64% (excluding GM) focused on six genera: *Pinus*, *Eucalyptus*, *Picea*, *Populus*, *Quercus* and *Acacia* (in descending order of recorded number of activities). 47% of all GM activities were based on a single genus, *Populus*. The number of genera allocated to different biotechnology categories were as follows: 99 genera for characterising genetic diversity; 82 genera for micropropagation; 40 genera for genetic maps, MAS and genomics; and 29 genera for GM. Allocation therefore by the end of 2004 were generally few. The exception was for micropropagation, for which important current commercial applications were noted, including in low-income countries. Generally limited outcomes to date apparently reflected the recent growth in biotechnology activities (research had not yet led to practical application, as for major crops), but also a lack of 'joined-up thinking' in project design. One factor appeared to be the poor coordination found between biotechnology and conventional applied tree breeding programmes. Perhaps of most concern in the present context (because of the wide applicability of techniques to lesser-studied genera), application of the large number of genetic diversity studies on forest trees to operational level field management of genetic resources appeared to be very limited.

Application of biotechnology to UPS

No review of biotechnology applications equivalent to that undertaken on forest trees (see above) has been conducted for UPS. In order to provide some feel for current biotechnology activity, therefore, we searched NCBI databases for references to species listed in Table 1 (see Table 1 footnote for further information). In the current context, the

Box 6. continued

indicated that certain biotechnology activities were more (genetic diversity) or less amenable (GM) to a range of taxa. Allocations appear to correspond with the level of investment required for different categories of activity.

Actual practical application limited (to date)

The review found that while expectations for biotechnology are high, actual cases of publicly cited commercial or practical field application by the end of 2004 were, for most categories of activity, only low. This partly reflects the recent growth in biotechnology activities (research has not yet led to practical application), but also appears to represent a lack of 'joined-up thinking' in defining wider objectives. The exception was for micropropagation (rooting of microcuttings, not yet somatic embryogenesis or organogenesis, although progress in somatic embryogenesis was seem as promising), for which there are current important commercial applications. The review found that rooting of microcuttings was used in > 20 species of commercial importance, including in low-income countries in Asia. In the future, somatic embryogenesis was seen as likely to become important for conifer propagation in high-income countries. For genetic diversity, the review found that, by 2004, many studies had been undertaken on trees, but very few obvious genuine practical applications at an operational level were evident (very limited obvious field implementation). The review found that genetic maps, MAS and genomics were seen as important for future commercial application, with massive investments made, particularly in areas such as wood quality. The entire *Populus* genome has been sequenced, and public and private EST libraries for conifers have more than one million entries. In addition, genetic linkage maps had been created for > 20 species. Gene discovery and association genetic studies are likely to become important practically (particularly with the long generation interval of trees). However, the review revealed little or no applied deployment of techniques yet. For GM, the review found that only one country, China, had undertaken commercial establishment by 2004, where plantations of *Populus nigra* (European black poplar), transformed with a *Bacillus thuringiensis* gene, to protect against leaf-eating insects, had been planted (review also found that approval in China had been obtained for *Populus* hybrids showing tolerance to saline conditions, a trait contributed by the MtlD gene from *Escherichia coli*). For GM activities, the review found that much work was being targeted to methods development and studying basic biology, rather than to direct commercial deployment objectives. When deployment objectives were being considered, the focus was on herbicide tolerance and biotic resistance (e.g. resistance to insect attack). For fruit trees, GM is likely to become important for tackling disease problems, to enhance rooting and to control fruit ripening.

Low integration with other disciplines

Generally, the review found poor coordination between biotechnology and conventional applied tree breeding programmes. For example, several GM projects had no connection to traditional breeding initiatives. Genetic diversity studies also failed to be linked to on-the-ground field management options.

FAO provides a range of useful information on biotechnology applications. The above review and other documents can be found at <http://www.fao.org/Biotech/>.

use of NCBI databases rather than standard reference searches has two main benefits. First, information held by NCBI is up-to-date and often precedes formal scientific publication of work, giving a feel for ongoing developments in what is a rapidly developing field. Second, NCBI provides world-recognised, centralised databases, which is of great benefit when dealing with a range of disparate species for which activities occur (and are reported) in a wide range of locations.

If we consider the total number of nucleotide sequence citations in NCBI as providing a good indication of DNA-based biotechnology research on species (which appears a reasonable assumption), then searches show a generally very low level of activity (Table 1). In fact, only 15 of the 30 taxa listed in Table 1 had 10 or more citations, while six species had no citations at all. Only five species had more than a modest 500 entries: *Chenopodium quinoa* (quinoa, 551 entries), *Eleusine coracana* (finger millet, 1773 entries), *Eragrostis tef* (tef, 2880 entries), *Ipomoea batatas* (sweet potato, 8314 entries) and *Sesamum indicum* (sesame, 3422 entries). The larger number of entries for these five species corresponds with the greater overall promotion research they have received, across all possible intervention areas (see Box 4), compared to other listed taxa. Sweet potato,

Box 7. Examples of biotechnology activities on UPS

In order to provide an indication of biotechnology activities to date on UPS, information, based primarily on NCBI citations, was collected on the 30 taxa listed in Table 1. Information below should not be considered as comprehensive; rather, listed activities can be seen as representative of work on these UPS. (See Box 3 for further information on biotechnology techniques.)

Tissue culture and micropropagation

Activities have been undertaken on a number of species, including *in vitro* propagation (normally via microcuttings or somatic embryogenesis) of *Abelmoschus manihot* (bele), *Aegle marmelos* (bael), *Coriandrum sativum* (coriander), *Ipomoea batatas* (sweet potato; *in vitro* samples used for the dispersal of germplasm; important in the production of transgenics), *Lablab purpureus* (hyacinth bean), *Plectranthus esculentus* (Livingstone potato), *Ricinodendron heudelotii* (ndjanssang) and *Sesamum indicum* (sesame). ARC-Roodeplaat have used tissue culture techniques to produce virus-free planting material of *Ipomoea batatas* and to rapidly reintroduce *Plectranthus esculentus* to small groups of farmers in areas of South Africa from which the species had been lost. In China's Shandong Province, a micropropagation project that created and distributed virus-free Ipomoea batatas was reported to have led to an increase in yield of up to 30 per cent, with considerable economic benefits apparently realised. Cryopreservation techniques are available, for example, for *Ipomoea batatas* (encapsulated shoot tips).

Characterising genetic diversity

Genetic diversity studies include on *Adansonia digitata* (baobab; AFLPs, within and among populations, combined with morphometric analysis), *Artocarpus heterophyllus* (jackfruit; isozymes, among accessions), *Bactris gasipaes* (peach palm; AFLP and isozymes studies, within and among populations; SSR development), *Diospyros kaki* (persimmon; SSR development), *Eleusine coracana* (finger millet; a wide variety of techniques, including isozymes, ISSRs, RAPDs and RFLPs, among accessions and related species; EST-SSR and EST-SNP development), *Eragrostis tef* (tef; AFLPs and ISSRs among accessions and related species, combined with morphological data; nuclear and organellar sequencing, among varieties, related and more distant species; EST-SNP and EST-SSR development), *Ipomoea batatas* (RAPDs, among accessions, combined with morphological analysis; SSR development; AFLPs and nuclear sequencing, among species), *Irvingia gabonensis* (dika nut; RAPDs, among accessions together with the related species *I. wombolu*), *Leucaena leucocephala* (leucaena; a wide range of studies using a range of techniques, among populations and related species), *Metroxylon sagu* (sago palm; AFLPs, among accessions and populations, combined with morphological analysis), *Sesamum indicum* (AFLPs among accessions; SSR development) and *Vitellaria paradoxa* (shea nut; isozymes, RAPDs, SSRs, within and among populations, combined with some morphometric analysis). Genetic marker techniques have been used to rationalise the *Ipomoea batatas* germplasm collection held by CIP. CIP used RAPD analysis to compare *Ipomoea batatas* accessions that appeared morphologically identical. Of those with identical RAPD profiles, one was selected to represent that group in 'living' collections. Duplicate samples were then converted to true seed and their clonal forms discarded. Using this approach, Peruvian accessions in the collection were reduced for example, is a priority species for the CGIAR 'HarvestPlus' Challenge Program, which, through biotechnology and other activities, seeks to improve the nutritional characteristics of a range of crop species.

In each of the five specific cases mentioned above, the majority of sequences represented ESTs (see Box 3), indicating intent to undertake genetic mapping, MAS and genomics work (see below). Putting these data in context, however, indicates how little research has been done even on these five taxa: EST figures for the major crops of maize, rice and wheat are more than 750,000, one million and 800,000, respectively.

Searching publication databases on NCBI for Table 1 taxa revealed a wider range of reports of biotechnology activities (Box 7). Tissue culture approaches have been practically deployed to a number of listed species, including for the distribution of breeding material between institutions, for virus elimination (with considerable economic benefits thus realised) and for enhancing manipulation. An interesting example is the deployment of tissue culture for the reintroduction of *Plectranthus esculentus* (Livingstone potato) to farmers in areas of South Africa from which the species had previously been lost.

Box 7. continued

from 1,939 to 673. A somewhat similar approach is currently being applied to *Eleusine coracana*. In a different kind of application, PCR primers have been developed to detect the 'fingerprint' of *Ceratonia siliqua* (locust bean gum) as a food additive.

Genetic maps, MAS and genomics

Activities for genetic mapping include on *Chenopodium quinoa* (quinoa), for which a linkage map based on AFLP, RAPD, and SSR markers was constructed to begin genetic dissection of agronomically important traits. Genetic linkage maps for *Lablab purpureus*, based on RFLP and other markers, have also been made. Genomic activities include EST generation for *Chenopodium quinoa* (SNP detection in candidate genes), *Eleusine coracana* (ESTs targeted to salt tolerance, drought stress and seed development), *Eragrostis tef* (and a wild relative), *Ipomoea batatas* (ESTs targeted to drought stress and storage roots) and *Sesamum indicum* (ESTs targeted to seed development). Expression profiles were compared between developing *Sesamum indicum* seed and *Arabidopsis* seed in order to identify EST candidates for genes that may be involved in the biosynthesis of sesame lignans (which have antioxidant and health protecting properties). Related work is concerned with creating more diverse fatty acid compositions in sesame oil, in order to make the oil more competitive in world markets.

Genetic engineering/modification

Genes involved in fatty acid synthesis in *Coriandrum sativum* and *Garcinia mangostana* (mangosteen) have been used to transform *Arabidopsis thaliana* and oil seed rape (canola), respectively, in order to understand metabolic pathways of seed oil production. Salt tolerance related to sorbitol accumulation has been studied in *Diospyros kaki* by transformation with a *Malus domestica* (apple) gene. Transgenic *Eleusine coracana* has been produced by various approaches, and an introduced gene from *Porteresia coarctata*, encoding a serine-rich-protein, has been shown to increase salt tolerance. *Leucaena leucocephala* was transformed with a gene from aspen that down-regulated lignin biosynthesis and may have a future role in the use of the species for pulp and paper manufacture, as well as in fodder production. Perhaps of most significance to date is work on transgenic *Ipomoea batatas*. For example, coat protein of the sweet potato feathery mottle virus has been introduced, with plans to introduce replicase genes of the same virus, in order to promote virus resistance. Yield losses through viral attack can be highly significant in some low-income countries where the species is an important staple. To date, field and other trials of transformed sweet potato, in Kenya and elsewhere, have indicated only partial success in introducing viral resistance. The development of GM sweet potato showing resistance to weevil attack is also under consideration.

Genetic diversity techniques appear to be the application that has been most widely used on listed species, perhaps on more than half of taxa (Box 7), reflecting the broad across-genera use also observed for forest trees (Box 6). A range of approaches has been employed, including more advanced methods based on SSRs, with EST-SSRs and EST-SNPs (see Box 3) also developed in some cases. Diversity studies have been applied mostly toward the assessment of variation within and among populations and between accessions, sometimes in combination with morphological analysis.

Actual practical application of diversity assessments is difficult to judge in most cases, but in several instances it is known (through personal involvement of one of the authors, IKD, on fruit trees) that, despite initial hopes, few operational level management options have been adopted based on results. It appears likely that this is also the case for several more of these diversity studies, reflecting a similar situation to the observations of the FAO review on forest trees (Box 6), where a lack of integration between biotechnology and other disciplines appeared to be a reason for limited development and deployment of field management options based on diversity analyses.

In some cases, however, diversity studies have led to real practical applications. For example, RAPD markers were employed by CIP in Peru to rationalise their sweet potato genebank, reducing Peruvian accessions in their vegetatively propagated 'core' collection by approximately two-thirds. This had important direct application because of reduced costs in collection management and in providing a form of pre-selection for breeding programmes. Similar approaches have been used for other UPS not listed in Table 1. Furthermore, the potential of diversity techniques for 'fingerprinting' the presence of diseases (and thereby excluding diseased material) during germplasm multiplication programmes, especially for vegetatively propagated UPS, could bring substantial practical benefits through increased yields.

Although work connected to genetic maps, MAS and genomics on Table 1 taxa is relatively limited and little (no?) practical deployment is yet apparent, the recent identification of ESTs in quinoa, finger millet, tef, sweet potato and sesame is interesting because of considerable future potential (Box 7). These ESTs could form the basis for a molecular breeding programme in these species, and in some cases may be applied to enhance capability to grow in very marginal environments, an important issue for some UPS (e.g. promoting drought and salt tolerance in finger millet).

Genetic variation associated with these ESTs could in the future form the basis for identifying candidate gene variation in pre-screens designed to incorporate potentially useful diversity into breeding programmes. In addition, variation in the same sequences, by being associated with DNA related to function, could form the basis for more effective *ex situ* collection rationalisation strategies (although focusing on 'neutral' or 'functional' variation in the establishment of core collections, and the concept itself of core collections, remain somewhat contentious issues).

One example where genomics and synteny (common arrangements of genes, especially across related organisms) could be exploited is in the breeding of blast resistance in finger millet, for which comparisons can be made with another grass, rice, where mechanisms of blast resistance are better understood and for which the genome has been sequenced (Naylor et al. 2004; Naylor and Manning, 2005). A similar transfer of knowledge from other major crops to UPS is also possible. A key limitation in the application of genomics to UPS will, however, be the lack of phenotypic characterisation of taxa, since understanding the complex link between the genetics and phenotype of an organism is essential for any genetic improvement programme. Of course, therefore, cases where biotechnology approaches build on existing more conventional UPS breeding programmes are likely to be more successful than those that do not.

Finally, GM activities on species listed in Table 1 have, perhaps, been higher than would be expected. Genes from UPS have been used to transform other species, and *vice versa*, in order, for example, to understand metabolic pathways, which may in the future bring some benefits to UPS use (Box 7). Potentially, UPS could form useful sources for the transformation of other crops, because their particular characteristics, a wide range of functions and high genetic diversity, could provide a wealth of useful genes. For example, it has been suggested that UPS with good micronutrient (vitamin and mineral) profiles could supply genes for the 'biofortification' of major crops (although this is not an approach that ICUC would strongly advocate, because it favours alternative action based around diet diversification).

Most GM activities on Table 1 taxa appear to be a long way from practical deployment, although work on sweet potato is perhaps an exception (Box 7). Here, sequences to promote sweet potato feathery mottle virus resistance have been introduced and field trials undertaken. To date, results indicate only partial success in protecting against virus attack, but future medium-term benefits could be highly significant. Developing GM sweet potato that is resistant to weevil attack is also under active consideration; in this case, conventional breeding approaches are limited because there is apparently little resistance to weevils in the sweet potato gene pool. Naylor et al. (2004) estimated that a reasonable adoption level of sweet potato GMs providing such resistance could bring considerable net benefits to sub-Saharan Africa (large benefits could likely also be realised in areas of the Pacific).

To summarise current deployment activities based on a survey of Table 1 taxa:

- Tissue culture and micropropagation activities are being practically deployed and are likely to continue to be highly relevant in the future.

- Genetic diversity studies are numerous, but practical application so far appears rather limited, perhaps suggesting that in a push toward the application of biotechnology, choosing relatively accessible (compared to other approaches) molecular genetic diversity techniques has not received sufficient critical attention to wider considerations. Practical application has, however, been realised is the case of *ex situ* collection rationalisation; further deployment in this area is likely (especially for vegetatively propagated crops), though it is only relevant for the rather limited subset of species for which significant *ex situ* collec tions exist. 'Fingerprinting' techniques for disease elimination in planting stock could in the future be highly beneficial.

- Genetic maps, MAS and genomics have yet to reach significant practical deployment, but their potential for a small number of more widely researched UPS is large; proper monitoring of the outcome of ongoing activities on these taxa will be very important, in order to judge future application for other species.

- Combining genetic diversity and genomic studies together, the screening of collections to identify candidate gene variation, diversity that may then enter into conventional and/or molecular breeding programmes, appears to carry considerable potential.

- GM activities have led to no current practical deployment, but ongoing work suggests that, for a small number of UPS, future impacts could be highly significant.

6. What are the difficulties, limitations and risks associated with the application of biotechnology to UPS?

Some of the difficulties and limitations associated with the application of biotechnology to UPS are obvious from previous sections. Many of these issues are interrelated, and include the following:

Caveats associated with biotechnology use include the high cost of some applications, limited capacity, inadequate integration and consumer resistance to some products. Biotechnology does not always fit well with some of the guiding principles of UPS promotion, including decentralisation, benefit sharing and the promotion of genetic diversity.

- Techniques are often expensive (infrastructure, consumables and salaries), drawing important and very limited financial resources from elsewhere.
- There is a lack of technical capacity (especially in low-income countries).
- Approaches suffer from a lack of integration with each other and with what can be a very wide range of disciplines for wider promotion.
- It is still too early for the net benefits of several biotechnology approaches to be tested through actual deployment (which would provide a proven baseline for new work).
- Lack of scientific knowledge for UPS regarding the control of important traits.
- Consumer resistance to some biotechnology products (in particular, GMOs).
- Work is often focused in and around the needs and interests of high-income countries.

In addition to these points, there are a number of more complex issues that need to be resolved that relate to the whole philosophy of UPS work in low-income countries. As described above (Section 4), UPS promotion in the tropics and subtropics is typified by a number of features, including the decentralisation of research, recognition of resources as public goods and equitable sharing of benefits, and the promotion of genetic diversity. These interrelated issues do not necessarily sit well with biotechnology approaches, as described below.

Issues of (de)centralisation

Much UPS promotion is concerned with farmer-led participatory research at the local community level. Biotechnology, on the other hand, generally (though not always exclusively) involves approaches that are applied in centralised laboratory facilities, which often (in the case of UPS) may be in other countries. The effect of this geographical separation between the different participants involved in promotion is that activities can become disconnected from actual practical needs. This is one explanation for the lack of integration sometimes observed between biotechnology and other promotion activities, with a subsequent gap between technology development and actual deployment. A good case in point is the lack of application of genetic diversity studies; taking Africa as an example, marker work has in the majority of cases been undertaken in laboratories in high-income countries outside the continent.

Another example where a 'disconnect' has led to inadequate attention to deployment is in the relationship between new 'biotechnology' varieties and germplasm delivery systems. Since delivery systems for UPS often rely on farmer-farmer linkages that are outside the control of the suppliers of new 'biotechnology' types, introductions to farmers can be more difficult than for conventional crops that are distributed through more formal supplier-to-farmer approaches. This may furthermore lead to mixed quality attributes at market level (hard to distinguish between existing and 'biotechnology' varieties at point of sale), discounting any 'added value' from biotechnology.

Finally, because of centralisation, product development may become more targeted toward international commodity markets, whereas more local markets may in many cases be more realistic targets for the sustainable promotion of UPS.

Public goods and equitable sharing of benefits

One consequence of centralised research activities is that the control that farmers previously had over the use of species (because of the large amounts of germplasm and knowledge that they held) is lost. Once material has been introduced into a centralised system that has only limited farmer access, there is often no guarantee that those initially supplying genetic material and associated knowledge on use will receive any significant benefits during 'commodity' development.

When commercial interests are involved, application for intellectual property rights (IPR) for the protection of biotechnology processes and modifications is likely, and these rights can play an important role in bringing the private sector into product development. In the worst scenario, however, IPR could mean that farmers are obliged to 'buy back' improved varieties, the raw materials of which they originally gave freely. In addition, the worst future scenario would involve proprietary ownership of biotechnology leading to certain markets essentially becoming monopolies; this would limit producer innovation (one company only controls the key use of products) and would unfairly fix product prices (limiting compensatory price changes associated e.g. with instability in production).

Promotion of genetic diversity

A characteristic feature of many UPS is their highly diverse gene pools. However, with notable exceptions (see below), biotechnology breeding approaches, for convenience of application and reasons of cost, generally involve the passage of germplasm through very narrow genetic bottlenecks, narrower than would be associated with more conventional breeding programmes. This is particularly the case where activities such as widespread cloning (micropropagation) of individual genotypes are involved in multiplication and distribution (cloning also being an important support activity for GM). Unless due consideration has revealed significant net benefits for biotechnology products, such a 'one size fits all' approach may have negative implications for many UPS in terms of potential for local adaptation and response to environmental changes (reduced potential across a range of different cultivation sites and lessened stability in response to adaptive pressures), in allowance for multiple uses (one use becomes favoured), and in providing a gene reservoir for future sustainable production and improvement ('dead end' narrowing of gene pools by displacement of existing more diverse cultivated types). One obvious exception to the above is when molecular marker techniques are used to characterise the extent and limits of diversity in taxa; this information could theoretically be used to bring real net benefits in enhancing management of currently wild and cultivated diversity for present and future use, in both *ex* and *in situ* environments.

7. Future actions for better application and considerations for ICUC involvement

Many of the actions required for better future application of biotechnology, and that can address some of the caveats associated with use, are clear from the above discussion. Needed actions can be divided into two main areas, the first concerned with developing partnerships and the second in relation to monitoring. Both areas are addressed below.

In order to effectively apply biotechnology to UPS in the future, better partnerships between different stakeholders involved in promotion activities will be required. Furthermore, examples of actual benefits realised during practical deployment are needed, based on rigorous monitoring of case studies.

Developing partnerships

Partnerships to improve technical capacity, spread biotechnology applications and information more cheaply, address IPR concerns, ensure better integration of activities, and overcome concerns linked to centralisation, are required if biotechnology is to be applied to UPS in a way that addresses the needs of the poor. Partnerships can be seen at a number of different levels, including between (Naylor et al. 2004):

- High- and low-income countries.
- Institutions working on major and lesser-used crops.
- The public and private sectors.
- Researchers and policy makers within low-income countries.
- The different participants in UPS product supply chains (all players involved in initial production through to consumer delivery).

Partnerships between high- and low-income countries can, among other benefits, help address the lack of capacity in breeding programmes in NARS. One relevant response in this respect is the Global Initiative for Plant Breeding Capacity Building launched in 2006 by FAO.

Partnerships between institutions working on major and lesser-used crops can, first, expose those working on major crops to the needs of UPS; second, explore the relevance of actual applications from major crops, based on approaches such as genomics, for UPS; and, third, expose those working on UPS to the information and other resources on biotechnology application that are already available through Internet and other databases.

Developing better links between public and private sectors should facilitate access earlier and at reduced cost to proprietary technology and products potentially useful for UPS promotion.

Better partnership between researchers and policy makers in low-income countries is needed so that the benefits and risks of biotechnology are properly incorporated into national development strategies, strategies where attention generally to both biotechnology and UPS is often currently lacking.

Proper partnership among the different participants in UPS product supply chains should ensure that biotechnology is always kept in a framework of ultimate deployment, that benefits are shared equitably (including with reference to farmers' and others' property rights), and that the wider context of farming systems is considered. This last point, by allowing protective and corrective measures to be taken where necessary, should at least ameliorate some of the concerns related to the impacts of deployment on farm biodiversity.

In all of these partnerships there is an important role for honest brokers, a function that the CGIAR centres and other international organisations such as ICUC, AVRDC and CABI, with their wide interests in biotechnology, training, information sharing, multidisciplinary research and other activities, all targeted to poor country development, may be in a useful position to help address. Initiatives such as the CGIAR 'HarvestPlus' Challenge Program, which is concerned with major and more minor crops, may offer particular opportunities. Important in any partnership is the potential for innovation provided by the interaction of researchers and other workers whom would not otherwise meet; for UPS, the meeting of biotechnology specialists with more 'generalist' promoters of these taxa is clearly essential in this respect, with the possibilities to realise novel solutions to old problems.

In recent years, a number of networks have been developed to share information and other resources on biotechnology between countries, institutions and sectors, several of which are relevant for UPS (see Box 8). While such initiatives, and other crop and regional networks, may play an important function in determining the future role of biotechnology for both UPS and major crop promotion in low-income countries, the emphasis on the commercial application of GM by several initiatives is, fairly or unfairly, viewed sceptically by an influential sector of the public. The apparent bias to GM causes mistrust and limits informed debate, hindering policy development and public acceptance of the wider issues related to future biotechnology deployment.

Monitoring biotechnology application

Current uncertainties on actual benefits in practical deployment mean that rigorous and objective monitoring of the outcomes of biotechnology activities is crucial in order to set a baseline for future work. It is clear from earlier sections above that a successful biotechnology intervention is much more than the development of a biotechnology product (such as an improved variety) itself; because of their particular characteristics, a holistic approach to monitoring, at different points along the product supply chain, is particularly important for UPS. Quantitative evaluation of the added value of biotechnology compared to existing more conventional breeding methods is required, the proportion of any benefit that is received by poor farmers needs assessment, the impacts of biotechnology interventions on other participants in product supply chains (seed suppliers, buyers, processors and consumers) is needed, and impacts on the environment (on-farm and landscape level diversity, sustainability) should be determined.

Whenever possible, monitoring of different case studies should apply the same indicators in order that proper comparisons can be made. Here, there is an opportunity for UPS: since real deployment is at an early stage, appropriate monitoring systems for cross-case study evaluation may still be put in place. Interesting case studies for monitoring include those involving genomics work on quinoa, finger millet, tef, sweet potato and sesame; although monitoring of these projects will inevitably include crop-specific elements, adoption of common indicators where possible could be extremely informative. Since many low-income countries have considerable experience in developing monitoring systems for other projects, there is much they could teach high-income countries on how to monitor the wider context of biotechnology applications, too. In a few years, a review assessing the actual deployment of biotechnology activities to UPS, somewhat similar to the FAO review on forest trees (FAO, 2004), would be useful.

Box 8. Networks for communication and collaboration

A number of networks to enhance biotechnology application, relevant for major crops and UPS, have been recently developed. Examples of these are described below.

ABNETA is an internet portal established by FAO to disseminate authoritative information and ideas to experts and the public on biotechnology for plant conservation and use in East and Central African countries.

APCoAB, supported by FAO, APAARI and a number of commercial biotechnology companies, among others, provides a forum in the Asia-Pacific region for improving dialogue with policy makers, creating better partnerships for research and application, enabling greater capacity building and generating public awareness on the uses of biotechnology.

AATF is designed to facilitate public-private partnerships in order to lower the transaction costs for the access and delivery of appropriate agricultural technologies in sub-Saharan Africa, by linking farmers with potential technological solutions that can be provided by commercial and other agricultural partners. AATF activities include acquiring technologies through royalty free licences with developers, partnerships with existing institutions to adapt technologies to African circumstances, and ensuring legal compliance connected to the use of technologies. Several commercial biotechnology companies, including Monsanto and Syngenta, have already agreed to provide varieties, patent rights and laboratory knowledge to African countries through AATF. AATF's aim is to take a wide view, addressing elements of production, distribution and market creation.

ISAAA, whose objectives are the transfer and delivery of appropriate biotechnology applications to low-income countries and the building of partnerships between institutions in high- and low-income nations, has centres in Kenya, the Philippines and the USA. ISAAA has built the Global Knowledge Center on Crop Biotechnology to collect and distribute information on all aspects of crop biotechnology to consumers, farmers, policy makers, scientists, and the media in developing countries. ISAAA will in the future commission independent impact assessment studies on crop biotechnology applications in low-income countries.

REDBIO is a large network in Latin America and the Caribbean that involves several thousand experts taken from a variety of organisations, and exchanges biotechnology information. REDBIO is supported by FAO.

ICUC's involvement in biotechnology

Although, for the reasons outlined in Section 6 above, practical deployment of biotechnology for the promotion of UPS is currently, and likely always will be, limited, there are important applications that can be realised, at least for a subset of species. The difficulty and time involved in realising these applications, however, will in many cases be greater than many technical specialists would have first considered likely. Thus, ICUC, when determining the institute's involvement, will carefully evaluate any proposals by national partners and other stakeholders when these include biotechnology activities. Particular attention will be given to the following points:

- Projects should give proper attention to the integration of biotechnology activities within the wider context of UPS promotion. This should go beyond statements of intent to actual integration of multiple disciplines within projects, with corresponding budget allocations (that is, projects which are 'biotechnology alone' will not be seen as priorities).

- Projects should clearly articulate the ways in which biotechnology activities relate to the needs of the ultimate beneficiaries, the rural poor. Ways to maximise benefits for the rural poor during intervention, compared to other players in the product supply chain, should also have received consideration.

- Projects should clearly state their relationship to practical deployment objectives. It should be clear that the development of these objectives has, at some stage, involved a participatory process of priority-setting, beginning at the farm level. It should also be clear that activities and projected deployment outcomes are based on as thorough a review as possible of both current promotion activities on a given UPS and of the biotechnologies that will be used. The position of activities within national development and biotechnology action plans should also be related.

- Projects should give due consideration to partnerships that will facilitate the likelihood of outputs being practically deployed. Projects should, as much as possible, provide for synergy between partners.

- Projects should state key indicators by which monitoring of biotechnology activities can be undertaken. In a large project, some facility for monitoring should be included.

- Projects should address issues related to intellectual property rights. At the very least, a statement that confirms adherence to legal requirements such as Material Transfer Agreements for plant material export (agreements which control future use) and a statement on whether or not IPR are likely to be applied for, by whom, and for what purpose, should be included. Where beneficial for the ultimate end users, information should, if possible, be held as a public good.

Key documents

Capacity Building International (2003) Underutilized Plant Species and Poverty Alleviation. International Workshop on Underutilized Plant Species, Leipzig, Germany, 6 - 8 May, 2003. Capacity Building International (InWEnt), Leipzig, Germany.

Dhlamini Z (2006) The Role of Non-GM Biotechnology in Developing World Agriculture. Science and Development Network (SciDev.Net), Policy Briefs. Available at <http: // www.scidev.net/dossiers/index.cfm?fuseaction=policybrief&dossier=6&policy=114>

FAO (2004) Preliminary Review of Biotechnology in Forestry, Including Genetic Modification. Forest Genetic Resources Working Paper FGR/59E. Forest Resources Development Service, Forest Resources Division. Rome, Italy.

Jaenicke H, Höschle-Zeledon I (eds.) (2006) Strategic Framework for Underutilised Plant Species Research and Development with Special Reference to Asia and the Pacific, and to Sub-Saharan Afrika. International Centre for Underutilised Crops, Colombo, Sri Lanka and Global Facilitation Unit for Underutilized Species, Rome, Italy. 33pp.

Naylor RL, Falcon WP, Goodman RM, Jahn MM, Sengooba T, Tefera H, Nelson RJ (2004) Biotechnology in the developing world: a case for increased investments in orphan crops. Food Policy, 29, 15-44.

Naylor R, Manning R (2005) Unleashing the genius of the genome to feed the developing world. Proceedings of the American Philosophical Society, 149, 515-528.

Science Council (2006) Enhancing the Delivery of Genomics Research Outcomes. Genomics Research in the CGIAR: Effective Means of Establishing Platforms for Genetic Research. CGIAR Science Council, Secretariat, FAO, Rome, Italy.

Acknowledgements

The authors benefited greatly from corresponding with a number of individuals and organisations in the development of this document. Special thanks are given for the assistance of Luigi Guarino, Peter Hedley and Joanne Russell in suggesting content and reviewing the manuscript. The financial support by the UK Department for International Development (DFID) to ICUC for the benefit of developing countries is gratefully acknowledged. The views expressed in this document are not necessarily those of DFID.

List of Acronyms

AATF	African Agricultural Technology Foundation
ABNETA	Agricultural Biotechnology Network in Africa
AFLP	amplified fragment length polymorphism
APAARI	Asia-Pacific Association of Agricultural Research Institutions
APCoAB	Asia-Pacific Consortium on Agricultural Biotechnology
AVRDC	World Vegetable Center
CABI	Commonwealth Agricultural Bureau International
CGIAR	Consultative Group for International Agricultural Research
CIP	International Potato Center
EST	expressed sequence tag
FAO	Food and Agriculture Organization of the United Nations
GFU	Global Facilitation Unit for Underutilized Species
GM	genetic modification (or genetic engineering)
GMO	genetically modified organism
ICUC	International Centre for Underutilised Crops
IPGRI	International Plant Genetic Resources Institute
IPR	intellectual property rights
ISSR	inter simple sequence repeat
ISAAA	International Service for the Acquisition of Agri-biotech Applications
MAS	marker-assisted selection
NARS	national agricultural research system
NCBI	National Center for Biotechnology Information (USA)
PCR	polymerase chain reaction
QTL	quantitative trait locus
RAPD	random amplified polymorphic DNA
REDBIO	The Technical Cooperation Network on Plant Biotechnology in Latin America and the Caribbean
RFLP	restriction fragment length polymorphism
SNP	single-nucleotide polymorphism
SSR	simple sequence repeat (or microsatellite)
UPS	underutilised plant species

The International Centre for
Underutilised Crops

ICUC Headquarters
PO Box 2075, Colombo, Sri Lanka
Tel: +94-11-2787404 Fax: +94-11-2786854
Email: icuc-iwmi@cgiar.org
www.icuc-iwmi.org