crop area expansion (Paarlberg 2001). This is not a sustainable solution for the continent's agricultural production problems.

Low agricultural productivity, rapid population growth and urbanization, diminishing reserves of unused arable land, extensive and increasing degradation of land (both soil and vegetation), and large deficiencies in food and nutrition—all these call for an accelerated agricultural productivity transition in Africa. They also imply that such a transition is unlikely without substantial changes in the technology of agricultural production. Thus the next phase of yield increases in African agriculture cannot ignore new techniques and products offered by biotechnology.

The new technologies

Modern technologies are indispensable in achieving the epidemiological and agricultural productivity transitions. They bring tremendous hope to those who live in fragile environments, depend on marginal lands, are exposed to health hazards and natural disasters, and have little coping capacity and almost no assets to fall back on in a crisis. But the new technologies are no panacea. They involve potential risks. And their benefits will not spread automatically to the poor and vulnerable. Minimizing the risks and realizing the full benefits of the technological revolution will require critical analysis and careful planning.

Medical (red) biotechnology

Modern biotechnology and genetics are expanding opportunities for developing new drugs and improving the efficacy of existing drugs and treatment. Genomics and its applications (genetic engineering) to health care—"red" biotechnology, in contrast to "green" biotechnology in agriculture and the environment—is creating a wide range of powerful new tools that are changing how common diseases are diagnosed, managed, and treated. These include gene therapy, DNA-based vaccines, and novel vaccine delivery systems. These new technologies are capable of enabling African countries to stem the devastation caused by the three leading causes of death—HIV/AIDS-related infections, malaria, and tuberculosis.

New applications of biotechnology to diagnostic tests are speeding and simplifying the identification of diseases, while advances in pharmacogenics are providing greater understanding of how the body responds to drugs, making it possible to develop more accurate and effective medication. Gene therapy holds promise for directly correcting genetic disorders, providing a cure rather than simply a treatment of symptoms of these disorders. And new genetic engineering techniques are revolutionizing vaccination.

Modern biotechnology is creating the possibility of soon developing vaccines capable of tackling a wider range of diseases, including sexually transmitted diseases, and with greater efficiency. Equally important are technological improvements to the delivery of existing vaccines. New forms of vaccines are being designed to overcome problems of access—scheduling, storage, stability, and cost. These new forms could avoid such requirements as the cold chain that is needed to keep vaccine doses at the correct temperature, which restricts the distribution of the oral polio vaccine.

Four new concepts for delivering vaccines are under development (CVI 1999; Fell 1998):

- *Naked DNA vaccines,* created by genetic coding for key antigenic components of viruses or bacteria.
- *Trojan horses,* produced by introducing genes into organisms that enable them to carry a vaccine into the body.
- *Edible vaccines,* developed by engineering seeds that produce plants capable of forming vaccines in their fruit or leaves and thus of acting as vaccines themselves.
- *Sugar glass vaccines,* kept in crystalline form so that they are easy to transport and store and can be "revived" with just a few drops of water.

With these innovative vaccine technologies, prospects for controlling and eradicating infectious diseases in the coming century are greater than ever.

Indeed, these and other advances in biotechnology offer hope that the three leading causes of death in Africa can be brought under control. A decade ago an HIV diagnosis was akin to a death sentence. Today the means exist to fight HIV/AIDS. Antiretroviral therapy is prolonging life and restoring health for HIV-infected individuals. Several HIV vaccines are showing positive results in advanced stages of clinical trials, including some directed towards the HIV strains prevalent in Africa. A malaria vaccine too may soon be developed, and research to transform the malaria-transmitting mosquito into a harmless insect has reached advanced stages. Beyond these, many other new discoveries in medical biotechnology fuel expectations of finding cures for many of the diseases directly implicated in Africa's poor economic performance. In short, these medical technologies have the potential to reverse the damage by HIV/AIDS, malaria, tuberculosis, and other diseases and put the continent back on the path of the epidemiological transition to sustainability.

Ethical issues in medical technology. Ethical concerns surrounding gene manipulation are so important that many countries, industrial and developing, have set up bioethics committees to determine general principles of research and application and monitor compliance with them.

The concerns are many. The potential impacts of human gene manipulation on research strategy and the enormous power conferred on the scientific community raise questions about rights to information and civil society participation. Major ethical questions also arise about equity and what is considered the common heritage of mankind. In particular, questions are raised about whether the ownership and economic benefits of gene discoveries can be privatized. These questions point to contradictions between the recognized right of intellectual property protection and the recognized universal ownership of genetic material, based on the principle that the DNA structure of human beings is the heritage of all and should be registered as the property of all.

Disequilibrium in research priorities. Worldwide, there is a huge disequilibrium between research devoted to the diseases of the poor and that focusing on the diseases of the rich: less than 10% of global spending on health research is directed to the health problems accounting for 90% of the world's disease burden—the 10/90 disequilibrium (Global Forum for Health Research 1999). As measured by disability-adjusted life years (DALYs), the global burden of communicable diseases, concentrated in low- and middle-income countries, is 13 times the global burden of non-communicable diseases, the main health concern of the developed world. Yet non-communicable diseases receive by far the most research attention, while communicable diseases are neglected. For example, malaria accounted for 2.7% of the global disease burden in 2000, with 90% of cases in Africa, but it accounts for only 0.17% of the $60 billion spent globally on biomedical research each year (CMH 2001; Global Forum for Health Research 2002).

This inequality in research is also reflected in medical products. Of the 1,233 drugs that reached the market between 1975 and 1997, only 13 were for tropical diseases (Global Forum for Health Research 2002).

Inaccessibility of new drugs. Two main factors are preventing Africa from benefiting fully from the new scientific and technological advances in medicine. First, African countries, with annual per capita health spending as low as $10, have difficulty purchasing vaccines and drugs. Thus even though the prices of antiretroviral drugs have dropped substantially, many African countries still cannot afford them. As a result fewer than 1% of Africans infected with HIV/AIDS have access to antiretroviral therapy today (UNICEF and others 2001).

Complicating the problem of the high cost of drugs are the generally weak health systems in Africa. The treatment and care of HIV/AIDS and tuberculosis patients require highly trained doctors and nurses to ensure strict compliance with the complicated drug regimens. But health systems in Africa are often poorly equipped to serve as effective conduits for care. About 95% of Africans infected with HIV/AIDS have no access even to basic health care.

Agricultural (green) biotechnology

The biotechnology or gene revolution is the third green revolution. It offers possibilities for further amplifying the gains from the first two through technologies involving reproductive biology and the manipulation of the genetic material of living organisms. These technologies cover a wide range, including molecular DNA markers, gene transfer, and vegetative reproduction.

Agricultural biotechnology is likely to have a significant impact in several ways:

- Improving the ability to diagnose plant and animal pathogens.
- Quickening the pace of research through new biotechnological techniques.
- Expanding the spectrum of potential products and traits through genetic engineering of plants and animals.
- Transferring genes from wild relatives of a crop as well as from unrelated crops.
- Improving the nutrient content of foods and thus addressing the serious nutritional problems of the poor.

Of particular importance to Africa are the recent advances in biotechnology that promise to produce crop varieties with higher yields, greater resistance to pests and disease, and better nutritional, health, and environmental attributes. The distinctive promise of the gene revolution for Africa is that it can provide a better way to extend productive potential to poor farm communities, pre-packaged in genetically engineered seeds rather than delivered haphazardly in many separate purchased inputs.

The gene revolution also offers the potential for reducing yield variability through improved pest and disease resistance. And it holds out possibilities of higher production on previously unusable lands through crops that can tolerate drought, salinity, and aluminum. Under the right circumstances, modern biotechnology could speed Africa's agricultural productivity transition to sustainability—and expedite reductions in poverty and food insecurity.

Exacerbate income inequality? Whether the potential benefits of genetically modified crops accrue to small farmers is a question of the type of technology and the degree of inequality in a country. Where land tenure reforms are implemented, there is support for small farmers, and other elements of a development-friendly environment are in place, a new technology can benefit all farmers. But where, say, 70% of the land belongs to 5% of the population and agricultural extension and credit services are available only to big landowners, a new technology will widen the income gap between large and small farmers. Thus the social and economic impact of genetic engineering and biotechnology can only be as good as the socio-political soil in which the resulting new varieties are planted.

Some types of biotechnology could deepen poverty in Africa. For example, commercialization of the terminator gene technology, designed to prevent seed reproduction and thus ensure repeated seed purchases, would harm the millions of small farmers who depend on replanting farm-saved seeds. These farmers simply do not have the money to buy new seeds each year. Critics argue that this technology removes one of the foundations of rural agriculture—forcing small farmers into colonial dependence on rapacious multinationals—and raise concerns about the spread of this trait to other plants. Proponents maintain that it is only a concept and that it is not being developed. But it is believed that terminator gene technology is now on the fast track to commercialization (RAFI 2000), though no products are planned for Africa.

Damage human and animal health? There is still no conclusive evidence to show that any of the transgenes found in genetically modified foods are harmful to humans. But one frequent concern is that if foreign genes were present in such foods at excessive levels, they could build up in the consumer's body, increasing the resistance of diseases to several types of antibiotics (Malcolm 1999).

Another potential risk is that people with allergies could suffer reactions after unwittingly consuming genetically modified foods containing allergenic proteins introduced from external sources (Altieri 2000). For example, someone who is allergic to peanuts might suffer a reaction after consuming genetically modified soybeans modified by the insertion of the peanut gene that produces the allergic reaction.

In fact, all the proteins that have been placed into foods through the use of biotechnology and are currently on the market are non-toxic; are sensitive to heat, acid, and enzymatic digestion (and thus rapidly digestible); and have no structural similarities to proteins known to cause allergies. Similarly, current evidence does not support the argument that inserting a new gene can alter the metabolism of plants and animals to produce allergens and toxins (Thompson 2000).

Some of these concerns have also been raised for animal health—concerns much publicized in the North, particularly in Europe. Livestock and poultry consume large amounts of genetically modified corn and soybeans, and some livestock producers have raised the prospect of antibiotic resistance. If genetically modified organisms lead to a buildup of antibiotic resistance, commonly used antibiotics might become ineffective, increasing the cost of maintaining animal health. Concerns have also been expressed about the risk that antibiotic resistance could be passed on to people who consume livestock products. No evidence has emerged to show that consumption of genetically modified feeds has affected animal health. But because such feeds have not been around long enough to carry out effective trials, it would be premature to conclude that the issue has been definitively resolved (Abelson and Hines 1999).

Degrade the environment? Probably the most controversial issues surrounding agricultural biotechnology relate to the long-term impact on the environment. The key issues:

- Whether genetically modified crops lead to genetic uniformity and, as a result, vulnerability to new matching strains of pathogens.
- Whether herbicide-resistant crops reduce agro-biodiversity.
- Whether cultivation of herbicide-resistant plants will result in super weeds by increasing the exchange of genetic information between crops and its spread to weedy relatives nearby.
- Whether *Bacillus thuringiensis* (Bt) crop hybrids destroy non-target insects, as Bt corn was thought to do to monarch butterflies (Losey, Rayor, and Carter 1999).

Only extensive, well-designed, and well-monitored field tests will provide conclusive answers to these questions. But the evidence so far is that the risk of environmental degradation is minimal (McGloughlin 1999). In the past 15 years researchers in the United States have conducted more than 4,000 field tests at 18,000 sites for efficacy, performance, and suitability for release into the environment (USDA/ERS 1999a). These and thousands of similar field tests in other countries have produced no conclusive evidence of danger to the environment.

Nor has biotechnology increased the vulnerability of germ plasm to homogeneous strains of pathogens or led to genetic erosion. For example, more than 1,000 Roundup Ready varieties of soybean are cultivated in the United States alone (USDA/ERS 1999a, b). But more impact assessment studies are needed to expand the empirical evidence, answer unanswered questions, and put the risks and benefits of genetically modified crops and foods into better perspective.

Reduce Africa's comparative advantage in tropical crops? With biotechnology, it will become possible to produce, in the laboratory or in temperate zones, crops that have been grown exclusively in the tropics. This prospect gives rise to concerns that the resulting competitive edge could drive many tropical products off the market. The common example is laboratory production of vanilla aroma, which could threaten the livelihoods of tens of thousands of small farmers in Madagascar, Uganda, and other African countries.

In cocoa production, genetically modified cacao seed varieties could raise yields and lower prices, dislodging smallholder production through plantation-scale farming in the newly industrialized economies of Asia. A similar outcome could occur for vegetable oils. And such countries as Mauritius, which depends on sugarcane for a large share of its export earnings, could find themselves hard-pressed if industrially manufactured low-calorie sweeteners supplant sugarcane.

The challenges—educate, innovate, regulate, deliver

Realizing the expected benefits of both medical and agricultural biotechnology in Africa is challenging in three respects.

First, some of the new technologies may not be readily applicable in Africa. This partly reflects the need for systematic provision of information and training to generate sufficient knowledge about the use of specific technologies. And it partly reflects the high cost of developing technologies and adapting them to a specific location. Effective exploitation of new technologies demands considerable investments in physical and human capital as well as institutions.

Second, biotechnology is not without potential risks, relating mainly to biosafety (risks to human health and safety and to the environment). Regulatory diligence is required, although available evidence suggests that such risks are minimal.

Third, the potential of biotechnology can be realized only if its innovations reach the ultimate beneficiaries. Delivering these innovations to poor and vulnerable individuals and communities (farmers, people suffering from HIV/AIDS, communities at high risk of malaria and tuberculosis infection) is thus as important as generating them.

In short, the successful use of new technologies depends on efforts to educate, innovate, regulate, and deliver—a course of action with mutually reinforcing components that should be embedded in the broad development strategy of each country.

Educate

Individuals—farmers, consumers, policy-makers, and scientists—are the agents and the beneficiaries of technological innovations. So, enhancing the capacity of these stakeholders to generate and adopt the new technologies is essential. There are two key parts to this:

systematic provision of information, and expanded training and education (formal and informal as well as general and specialized).

First, knowledge has to be systematically generated and disseminated about the technologies and about their appropriateness to African communities where they are going to be used. Information needs to be provided to all stakeholders about the benefits and risks of the technological innovations. Equally important, knowledge should be furnished about the needs, endowments, and constraints of target communities, particularly to policy-makers and research and development specialists. Such systematic generation and provision of knowledge is particularly essential for the new innovations in medical and agricultural biotechnology, given the impassioned debates about the biosafety, food safety, and other risks.

Information contributes to the successful adoption of these technologies in a number of ways. It helps potential users (such as poor farmers, consumers, and patients) and policy-makers to set priorities for research and development, particularly for the choice of crops and desirable traits, disease targets and treatments, and product delivery systems. It also helps researchers and product developers tailor their efforts to the needs of their target population (poor farmers, for example) in a way that reflects local endowments and constraints. The benefits from effective participation of stakeholders and context-specific innovations cannot be overemphasized.

Second, the stock of human capital in Africa needs to be further expanded and deepened. Human capital makes two critical contributions. It is a major determinant of the continent's capacity to absorb the knowledge associated with new technologies. And it is an essential input into the creation of new knowledge and technologies appropriate to the region. So, general education needs to be expanded to boost the analytical and adaptive capacity essential to the adoption of technologies. Advanced or specialized training is also indispensable, to build the expertise required for developing, regulating, and delivering biotechnology products. Education investments and curricula should reflect these demands.

Innovate

Research and development efforts in medical and agricultural biotechnology have been concentrated in industrial countries, with most conducted or funded by private companies motivated primarily by profits. As a result most biotechnology products are intended for use in industrial countries and controlled by a few multinational corporations. The evolving system of intellectual property rights complicates the situation by extending protection to certain types of innovations (such as the isolation of a gene, protected by a patent) while ignoring others, particularly indigenous knowledge and biodiversity. These circumstances call for technological and institutional innovations if Africa is to reap the benefits of biotechnology.

African countries need to direct their research and development efforts towards filling the gaps created by biases in multinational-led research and development, making advances in biotechnology relevant to African countries and their poor citizens. One urgent concern is HIV research and vaccine development focused on the strains of the virus prevalent in Africa. Much attention should also go to research on staple foods in African settings, local resource-intensive technologies, and crop and animal traits relevant to poor farmers.