Frontiers in Crop Production: Chemical Research Objectives

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The science of chemistry and chemicals has been an essential element in achieving the remarkable increases in agricultural productivity which have been observed during the last half century in the industrialized and also, to some extent, in developing economies (*1*). Chemicals will continue to be an integral part of agricultural and food processing technologies in the global efforts that will be required to cope with the challenging objectives, problems, and opportunities of providing sufficient food for the burgeoning world population. However, when one is assessing and defining the future role of chemistry it is essential to refrain from making simple linear projections of current inputs and to consider the following three imperatives.

Summary. The science of chemistry and chemicals will continue to be an integral part of future crop production technologies. In assessing and defining the future role of chemistry three imperatives must be considered: (i) the necessity to preserve natural resources, (ii) the complementary solutions offered by the rapidly advancing biological sciences, and (iii) the specific requirements of developing regions where increasing crop productivity is most important. Chemical research objectives for improving crop protection and crop growth must take into account the perceivable and potential changes in crop production techniques, which, in turn, are dictated by a number of accentuating constraints.

1) The worldwide potential of (eco-)biological systems to provide resources—such as energy, land, water, and air—continues to be eroded. These resources must be conserved by reducing environmental stress and by improving resource management (*2*).

2) The current and forecasted extraordinary advances in the biological sciences appear to offer complementary or alternative technical solutions to a number of agricultural problems (*3, 4*). Therefore, chemistry must be closely integrated with or adapted to biological approaches in order to achieve optimum effects and efficiency.

3) In order to meet the exacting future food requirements, scientific and technical efforts must be focused on increasing agricultural productivity in the developing countries. This means that the use of chemicals must be adapted to the particular environmental, economic, social, and institutional conditions prevailing in these areas.

The coming IUPAC/IRRI-CHEMRAWN II International Conference on "Chemistry and World Food Supplies—The New Frontiers" will attempt to place these imperatives into proper perspective and to generate recommendations concerning the required research objectives and priorities (*5*). In this article we focus on a number of scientific and technical trends and opportunities in crop production.

Development in Crop Production Technology

The chemical research objectives we describe herein cannot be defined properly without taking into account the perceivable and potential changes in crop production technology, which, in turn, are dictated by a number of accentuating external constraints. The results of properly selected research objectives can contribute to alleviating some of these constraints and thus facilitate or permit the introduction or extension of different crop production techniques.

The major current and anticipated constraints of crop production and some of the extending or emerging technologies are summarized in Table 1. In order of priority, soil erosion (deterioration), increasingly erratic water supplies, rising energy costs, and progressive contamination of the environment (water, air, and soil pollution) are the commonly noticed and rapidly accentuating major constraints of present and future crop production (*6*). Techniques to counteract or overcome one or more of these constraints include conservation tillage, different modes and practices of mixed cropping, modified irrigation procedures, and improved pest management systems.

The vulnerability of crops to adverse climatic and meteorological conditions not only causes frequent crop failure and harvest losses but also prevents a significant extension of the global surface of arable land and a shift of more productive crops to new areas. Techniques that can help to overcome climatic vulnerability are proper irrigation and, provided they can be economically and scientifically improved, "greenhouse" cropping (including foil coverage of sensitive crop stages), hydroponics, and nutrient film techniques (*7*).

Optimization of inputs into crop production and modeling of input/output ratios will be greatly facilitated by systematic exploitation of the rapidly advancing electronic data evaluation and processing techniques. If accompanied by improved sensoring and monitoring of environmental parameters and conditions, this will allow a gradual sophistication and extension of "systems" agriculture (*8, 9*).

Rising agricultural production and increased mingling of agriculture with densely populated nonagricultural areas will accentuate problems of agricultural wastes. These problems must be overcome through technical and economic progress in agricultural recycling procedures (*10*).

It is evident from the above comments that now, even more than in the past, chemical research objectives in crop production must be closely correlated with changes and advances in agronomic practices and techniques.

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Crop Protection

Crop losses due to insects, plant diseases, weeds, nematodes, and rodents continue to be a major threat to the productivity of many important world crops, especially those grown in developing countries (*11*). Because of their efficiency and economy, synthetic pesticides will continue to be an essential factor in future pest management strategies.

During the recent past, the properties of synthetic pesticides have been significantly improved, so that they can now be applied in reduced quantities, they are more selective with regard to nontarget organisms, and their behavior in the environment has been ameliorated. However, reliance on chemicals as a single line of defense also has created problems of pesticide resistance, suppression of natural pest enemies, and outbreaks of secondary pests. In order to avoid perceived and potential contamination of the environment and adverse health effects, synthetic pesticides have been subjected to increasingly stringent regulatory constraints (*12*).

For future efficient and judicious employment of chemicals in pest control, it is imperative to improve their inherent biological properties, their formulations, the way in which they are applied, and the tactics of their use. This last form of improvement includes finding methods of combining pesticides with appropriate supplementary and alternative control methods. The main research objectives resulting from these integrated approaches are summarized in Table 2.

Insect control. The search for substances that induce pest-specific biochemical lesions or that regulate natural control mechanisms is most advanced in the area of insect control. The discovery of diflubenzuron [1-(4-chlorophenyl)-3-(2,6-difluorobenzoyl)urea], an insecticide that acts by interfering with the synthesis and depositing of chitin, a major constituent of the insect exoskeleton, has spurred intensive synthesis programs. New derivatives of this compound and related structures are likely not only to be nontoxic to certain beneficial pest predators and parasites, but also to have spectra of activities that cover additional pest species of economic importance (*13*).

Although research on endogenous insect juvenile hormones and their synthetic mimics (juvenoids) has not, thus far, led to extensive practical applications, it appears that their potential, especially when they are used in combination with other insect control methods, has not been fully explored. However, as their activity is confined to a short and specific period of insect development, their utility in controlling mixed populations under field conditions is likely to remain limited. Therefore, attention has turned to insect antijuvenile hormones (hormone antagonists, antiallatotropins). These compounds, of which the precocenes are but one example, cause precocious metamorphosis and sterilization and appear to be more versatile in their use than juvenoids (*14*).

Research on the chemistry and biology of insect pheromones, that is, natural and synthetic chemicals which, as attractants, repellents, or "disruptants" affect insect behavior, continues at a high rate. Innumerable compounds have been isolated or synthesized, and examination of their biological effects has revealed a bewildering and complex pattern of insect communication systems. Although practical applications have thus far been limited to surveying and forecasting pest infestations and to the localized control of some insect species in forests, fruit crops, and public hygiene, more extended uses can be envisaged, especially where the physical problems of targeting, release, and timing are resolved (*15*).

From among the countless entomopathogenic (insect-destroying) fungi, bacteria, and viruses, some have already been developed into selective, commercial insecticides. The search for additional preparations of this kind is likely to reveal products with improved efficiency and more useful spectra of activity. Modern biotechnology and genetic engineering methods appear to be excellent tools for substantial technical and economic improvements in microbial insecticides (*16*).

Further areas that seem to open new avenues in insect control, but that have not yet been sufficiently explored with regard to their practicability, are natural antifeedants from insect-resistant plants, insect-specific neurotransmitter agonists or antagonists, and insecticidal antibiotics and antibodies (*17, 18*).

Plant fungal diseases. The control of fungal diseases is at present dominated

Table 1. Perceivable and potential development in crop production technologies as dictated by accentuating environmental constraints.

Constraint	Crop production technique
Soil erosion, soil degradation (sedimentation, desertification, salinization, for example)	Conservation tillage (reduced or no tillage)
	Mixed cropping, including inter-, cover-, and avenue-cropping
Water shortage	Minimum irrigation: for example, drip or trickle irrigation and "chemigation"
Energy costs (shortage)	Energy farming, including silviculture
	Integrated pest management, including increased biological control
Environment contamination	"Greenhouse" cropping
	Hydroponics, nutrient film technique
Climatic vulnerability	"Systems" agriculture, including electronic monitoring, data evaluation, and input control
Agricultural wastes	Recycling

Table 2. Major research objectives for maintaining and improving the future use of chemicals in crop protection (pests here include diseases and weeds).

Continue and accelerate search for selective, biodegradable compounds that rely on pest-specific biochemical lesions or natural pest-controlling (pest-inhibiting) mechanisms

Attempt to delay or eliminate induction and appearance of resistance to pesticides by appropriate use-tactics or by systematic interference with resistance mechanisms

Improve application technology for pesticides by more specific placement, timing, and targeting

Extend and ameliorate integrated pest management systems by
- a) Research on the biology of pest development, pest-population dynamics, pest-host relationships, and interactions among pests
- b) Development of appropriate forecasting techniques by determining economic thresholds and designing monitoring methods and devices
- c) Combining synthetic pesticides or growth regulators with suitable cultural, biological, physical, pest-genetical and plant-breeding methods
- d) Modeling of area-specific or crop-specific pest-management strategies by systems analysis and programming, including use of electronic data evaluation and processing devices

by chemicals that either destroy the pathogen itself or are converted into toxic derivatives by the pathogen or host plant tissues. The recent discovery of a number of highly efficient, selective, and systemic fungicides, such as the triazoles and acylalanines, has set new standards among these chemicals and their range is likely to be expanded further. However, research has started to turn to areas that are likely to offer alternative chemical approaches to disease control. Essentially these endeavors attempt to elucidate and exploit the numerous existing natural biochemical interactions between pathogenic (or nonpathogenic) organisms and their host plants. Such reactions, which determine expression (or suppression) of disease phenomena, are being investigated along the following lines.

1) The interference with components of pathogenic processes (enzymes or toxins, for example) that are involved in breaching external and internal defenses of host plants.

2) The induction (activation) of phytoalexin formation, that is, the mobilization of the plant's own localized cellular defense system both by biotic and abiotic "elicitors."

3) The induction of systemic host plant resistance by inoculation with or exposure to pathogenic and nonpathogenic organisms or their extracellular metabolite fractions.

Although these approaches reflect the different defense or resistance mechanisms that seem to occur in plants, it is possible that they represent interlinked components of a more general phytoimmunological system against diseases and pests that might be manipulable both by chemical and genetical means (*19*).

Weed control. In most crops and under most cultural conditions, weeds include mixed populations of a variety of annual and perennial broad-leaved plants and grasses. Though the present armament of pre- and postemergent herbicides is already impressive, it is in the process of being further extended and improved by the addition of new compounds that are active at significantly lower rates of application. This trend is best exemplified by the recent discovery of the sulfonyl ureas (*20*). The ongoing systematic search for herbicide "antidotes," "safeners," and "synergists" has started to yield results and can be expected to provide an increasing number of chemicals that increase the selectivity and efficiency of conventional herbicides and permit lower rates of application (*21*). In order to delay soil erosion, it is envisaged that, under certain agronomic conditions, weed canopies will no longer be completely destroyed by herbicides but controlled by appropriate plant growth regulators. The possibilities of exploiting or copying natural defense systems against weed growth, such as allelopathy (release of growth-inhibiting substances from higher plants) or biological agents (plant-killing microorganisms) appear to be limited to particular weed populations or habitats where it suffices to eliminate one or a few closely related weed species (*22*).

Resistance. Attempts to delay or prevent resistance of insects and crop pathogens to synthetic pesticides have, in practice, not been very successful. However, research in the physiology and biochemistry of resistance mechanisms has accelerated and should allow more rational approaches to controlling resistance phenomena. The tactics initiated or envisaged include the mixed or alternating application of compounds with distinctly different modes of action, the addition of chemicals that antagonize the induction of resistance, and the deliberate search for control agents that affect the proliferation of insects and pathogens at growth stages that are less inducive to the formation of resistance (*23*).

Application technology. Although application technology for pesticides has been continuously improved, the currently available formulations and delivery systems are still somewhat inefficient. This can be demonstrated by comparing the amounts that are normally applied with the small quantities that eventually reach the envisaged target organisms. More efficient targeting is to be expected from improving controlled release formulations and devices, from more sophisticated coating or encapsulation of seed, and from improving spray equipment physics (*24*).

Integrated pest management. Recognition of the shortcomings mentioned in the unilateral use of chemicals in crop protection has accelerated the conception and implementation of integrated pest management (IPM) (also referred to as integrated pest control). This "systems" approach to crop protection combines, in an organized manner, all forecasting and control components that can efficiently and economically contribute to crop protection in a particular and defined crop or agro-ecosystem. Figure 1 depicts the essential elements of IPM and their interactions. Further extension of IPM in terms of acreage and crops will proceed stepwise and will depend heavily on the generation of additional biological and agronomic research data that are not now available. These data will also assist in improving the timing and targeting of chemical IPM components and in the identification or design of new and more selective compounds (*25*).

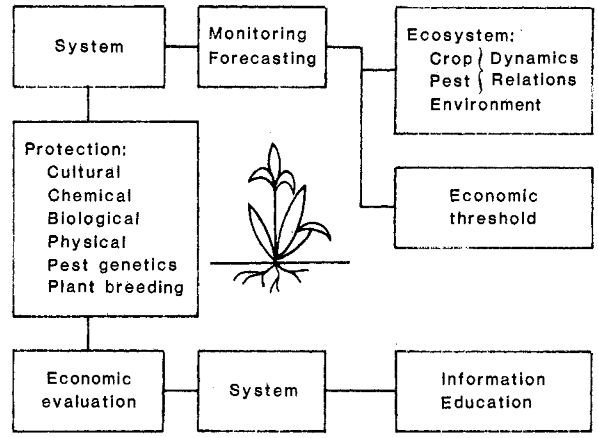

Fig. 1. The major components of an integrated pest management system and their sequential interlinkage. Recognized features of the defined crop ecosystem, such as crop-pest relations, allow the determination of an economic threshold (pest or disease level above which a loss will occur that is greater than the cost of a particular control action). These components are essential for proper monitoring and forecasting and for timely protection. Systems modeling can be performed at different stages of the integrated pest management procedures (*25*).

Crop Growth

The required gains in overall crop productivity (that is, increasing average crop yields per unit area) can only be achieved through improved control of crop growth and development. The extension and perfection of currently used principles and methods, and the design and introduction of new agronomic, biological, engineering, and chemical concepts and tools are needed to secure more, and especially more efficient, inputs of solar energy, carbon, nitrogen, and minerals, for example, and more efficient utilization of available water and land resources. Some of the research objectives to improve and extend contributions by chemistry to crop growth and development are summarized in Table 3.

Plant growth regulators. Basic and applied research in plant growth regula-

Table 3. Major research objectives for improving crop growth and development by chemicals or chemistry-based concepts.

Rationalize the search for new plant growth regulators by acquiring additional basic knowledge on the regulation and interactions of phytohormonal systems at different stages of (natural) crop growth and by defining more precisely the physiological target mechanisms to be controlled

Extend the acquisition of basic information on photosynthetic carbon assimilation to those factors or mechanisms that limit efficiency in major crop plants under natural growth conditions. Exploit this knowledge for more rational chemical, genetical, and cultural approaches for regulating respective key processes

Improve the efficiency and economy of different components of the nitrogen cycle by
- a) The identification or biorational design of new catalysts for nitrogen fertilizer production
- b) The development of economical processes for nitrogen recycling from wastes
- c) The control of biochemical mechanisms that regulate photosynthetic energy flow to nitrogen-fixation processes, the distribution of protein components in plants, and the mobilization of nutrients by mycorrhizae
- d) The improvement of control agents that inhibit wasteful nitrogen transformation processes in soil

Accelerate the acquisition of basic knowledge on the terrestrial biosphere, especially the crop "rhizosphere," to improve the efficiency of nutrient and trace element additions

Adapt the delivery of chemicals to conservation irrigation systems

tors has been slow in producing tangible practical contributions toward increased productivity of economically important crops. The intensive efforts to exploit chemical and physiological features of naturally occurring phytohormones (auxins, cytokinins, gibberellins, abscisic acid, and ethylene, for example) and empirical screening procedures have resulted in a number of chemicals that are used for a variety of horticultural and agricultural purposes. The physiological effects obtained include rooting, flowering, fruit setting and abscission, ripening, bud and sprout inhibition, dwarfing, and defoliation. These effects, which are based mainly on controlling inhibitory plant growth mechanisms, contribute only indirectly to increased crop productivity. However, it is accepted by most experts that they represent only a small portion of the potential for chemical growth regulators in crop production. The main reasons for the slow progress in this area appear to be the following: (i) a continuing lack of basic knowledge on how phytohormones interact and how crop growth is actually regulated at different stages of development, (ii) imprecise definitions of the goals, that is, the physiological mechanisms to be controlled, and (iii) genetic and environmental variability of target crops (*26*). To reach demanding objectives such as yield enhancement, growth promotion under stress conditions, and control of senescence, both basic and applied research must be accelerated and also concentrated on the following essential aspects:

1) Identification of natural growth regulator mechanisms (phytohormones) in addition to those already described; and the interactions of these mechanisms at different stages of crop growth and development.

2) Determination of rate-limiting regulatory mechanisms or interactions in major crops under representative agronomic (field) conditions.

3) Precise definition of physiological target mechanisms to be controlled and translation into appropriate screening or modeling procedures.

4) Improvement of coherence between laboratory or greenhouse and field testing.

It may be assumed that many industrial laboratories are already involved in tackling some of the described phenomena, but this does not reduce the need for extended parallel contributions by universities and government laboratories which are indispensable.

Photosynthetic carbon assimilation. The central role of photosynthetic carbon assimilation in crop production is demonstrated by the fact that carbon input provides 90 to 95 percent of the dry weight of crop plants. The photosynthetic electron transport mechanisms and carbon assimilation reactions involved have been elaborated in impressive detail. However, attempts to improve carbon input efficiency under agronomic conditions by manipulation via chemical or biological means have not been very successful. Rationalization of future approaches and the design of appropriate testing models requires the acquisition of additional basic knowledge (*27*). These efforts must concentrate on a detailed characterization of the particular features of photosynthetic assimilation systems of major crop plants and on those factors or mechanisms that limit or control the efficiency of these systems under natural growth conditions. As this basic knowledge becomes available, more rational approaches can be taken for regulating by chemical, genetical, or cultural means key processes such as light conversion, carboxylation reactions, dark and light (photo-) respiration, photosynthate partitioning and transport, and leaf senescence (*28*).

Nitrogen. The input of nitrogen as a fertilizer has been essential to achieving the current levels of crop productivity. Future agricultural needs will require substantial increases in the production of this major nutrient. However, there are serious constraints (energy costs, capital requirements, environmental impact) which call for significant improvements in the efficiency and economy of nitrogen production and utilization and also for the extension and improvement of alternative nitrogen input techniques (*29*).

Chemical research objectives to ameliorate the efficiency of the various components of the nitrogen cycle include the following:

1) The identification or biorational design of catalysts that permit the production of fertilizer (fixation of dinitrogen) at reduced temperatures and pressures.

2) The improvement of existing processes and the development of new low-cost processes to recover nitrogen from agricultural wastes.

3) The regulation of the biochemical mechanisms involved in providing photosynthetic energy from leguminous crop plants to symbiotic or associated nitrogen-fixing microorganisms.

4) The extension or improvement of control agents that inhibit wasteful soil nitrogen transformation processes, such as microbial nitrification or denitrification and soil urease activity.

5) The design and development of low-cost controlled-release fertilizers.

6) The control of the biochemical mechanisms that regulate the transport of protein components to edible crop parts.

Exploitation of new or improved chemical tools or processes for nitrogen utilization requires integration with novel agronomic and biological techniques.

Other nutrients. The input of nutrients other than fixed nitrogen must be extended and improved under the same constraining conditions as described above. Much more basic knowledge in the terrestrial biosphere and on the microenvironment of the crop "rhizosphere" is required before more efficient use of such major nutrients as phosphorus and potassium can be made and before the addition of trace elements can be optimized (*30*).

In exploiting this knowledge, attention should not only be directed toward optimum soil conditions, but even more so to the widespread arid and semiarid areas, where soil improvement by massive additions of fertilizer is not only uneconomical but also of questionable value. The alternative strategy of adapting crop growth to adverse soil conditions (for example, drought and salinity) on the basis of chemical concepts must be pursued further (*31*).

Water. A shortage or an excess of water is the most common limiting factor in world crop production. The extended and improved management of water resources will depend mainly on operations and engineering technology. Potential contributions by chemistry are indirect or secondary. Thus, chemistry will continue to be involved in seawater desalination projects and can also contribute to the prevention of soil salinization and reclamation of saline or sodic soils. Sophisticated water management techniques are likely to offer new opportunities in modifying and economizing on the application or delivery of chemicals to crop plants and soils (*32*).

Table 4. Major research objectives for improving crop growth and development by modern biotechnology (including genetic engineering).

Elaborate or improve the scientific and methodological components of crop plant biotechnology, for example, gene transcription, transfer, and expression mechanisms, protoplast fusion and foreign vector transfer, and regeneration of plants from single cells
Modify current species or design new crop species by gene manipulation in order to improve growth features, nutritional quality, and resistance to plant pests and diseases
Use gene manipulation techniques for improving the efficiency of microbial crop symbionts or associates and for extending the range of useful organisms
Improve fermentation processes for the production of biologically active agricultural products or organisms, including, for example, microbial pest and disease control agents

Biotechnology, Including Genetic Engineering

Recent advances in gene manipulation have opened new avenues in agricultural research and have added a new dimension to the future of crop production (*3*, *33*). Though the developing genetic technologies are considered to be a part of the biological sciences, chemistry is involved in or affected by these activities in several ways:

1) Chemistry is an indispensable tool for acquiring or extending the necessary basic knowledge and for perfecting methodology.

2) Gene manipulation techniques have the potential of ameliorating microbial or other single-cell fermentation processes for the manufacturing of biologically active agricultural chemicals and products.

3) Biotechnology offers opportunities and eventually solutions that can complement conventional chemical means and approaches in agriculture.

For these reasons, biotechnology has been included in the agenda of the forthcoming CHEMRAWN II conference and is briefly discussed herein. The following areas of biotechnology appear to be relevant in order to increase or improve crop production: (i) genetic improvement of crop plants; (ii) genetic improvement of microbial crop associates including symbionts and pathogen antagonists; and (iii) genetic improvement of fermentative processes for the production of crop protectants and growth regulators, for example. A summary of pertinent research objectives is given in Table 4. These objectives emphasize the complementary nature of biological and chemical approaches.

Genetic improvement of crop plants. For the genetic improvement of crop plants the new cell- and gene-manipulating techniques are suited to the expansion and complementing of conventional breeding methods. They allow circumvention of the classical barriers of genetic incompatibility and acceleration and perfection of the process of genetic refinement and propagation. However, before useful results on important crop plants can be expected, the following scientific and technical components must either be elaborated or improved: (i) identification and mapping of genes and characterization of their transcription and transfer mechanisms; (ii) protoplast fusion or foreign vector (plasmid, virus) transfer of DNA sequences into plant cells; and (iii) regeneration of whole, genetically stable plants from individual cells. Modified or even new crop species obtained by gene manipulation may be designed to exhibit improved growth features, such as more efficient photosynthesis, nitrogen-fixing capability, and tolerance to stress conditions; improved nutritional quality; and (multiple-gene) resistance to plant pests and diseases.

Genetic improvement of microbial crop associates. Recombining DNA among microbes is less complicated and more advanced. This technique may therefore be exploited for the genetic improvement of microbial crop symbionts or associates, such as bacteria, cyanobacteria, actinomycetes and fungi, which live in, on, or in the vicinity of plant roots and which are able to supply the crop in situ with desirable nutrients, such as fixed nitrogen and phosphorus. In addition, microbial antagonists might secure vigorous growth of roots by protecting them against pathogens (*30*, *34*).

Genetic improvement of fermentation processes. The future use and genetic improvement of industrial fermentation processes for the production of biologically active agricultural chemicals will depend on a number of external stimuli, including the scarcity of classical supply sources, the availability of potentially useful and cheap raw material, and the discovery or design of new biologically active and selective entities that cannot be economically produced by conventional means. Examples of products that can be envisaged to meet these criteria are microbial and antibiotic crop protectants (insect and disease control agents) and plant growth regulators (*16*).

Objectives for Developing Regions

Political, socioeconomic, institutional, and educational factors will be the main influences on the extension and introduction of chemistry and chemicals for improving crop productivity in the developing regions. In the technical area, the enlargement of local research capacities, extension services, and training facilities will be essential (*35*, *36*). The activities of these institutions must concentrate on problems and opportunities related to native crop species and to local cultural and growth conditions, as well as pest and disease phenomena.

The small farmer. While the transfer and adaptation of current and future industrialized agricultural technology is indicated for plantation and estate crops, it appears that a distinctly different scientific and technical approach will be required for improving and stabilizing the productivity of the small farmer, who is and must continue to be the central figure in cultivating staple and subsistence crops. The so-called "intermediate" techniques to be further developed and perfected for this purpose must be low in cost and energy, simple, safe to health and environment, and nondestructive to natural resources (*37*). The key elements of these techniques are genetically adapted high-yielding seed materials, appropriate cropping practices (for example, mixed, inter-, relay-, or avenue cropping, including the use of leguminous vegetables and tree crops) and conservation, tillage, and irrigation procedures. Chemicals, as fertilizers, trace elements, herbicides, insecticides, and growth regulators, will have to be exploited in a complementary or incremental manner to achieve defined beneficial effects. The tools and methods used for their application must be simple, reliable, and independent of logistical constraints (*38*).

Conclusions

We have attempted to describe and define chemical research opportunities, which, if explored and pursued systematically, can be expected to contribute further to the improvement and stabilization of future crop production. Technical solutions can already be identified for some of the objectives mentioned, whereas for others, further progress in basic research is essential in order to define more precisely those avenues to be followed toward ultimate practical success. This emphasizes the need for unbiased, straightforward, and close cooperation between academic, governmental, and industrial scientists and institutions from numerous countries. It is hoped that the coming CHEMRAWN II conference will be able to maintain and improve this cooperative spirit through its efforts to define objectives and priorities for the judicious use of chemicals to ensure adequate world food supplies.

References and Notes

1. D. L. Gunn and V. G. R. Stevens, *Pesticides and Human Welfare* (Oxford Univ. Press, Oxford, 1976); United Nations Industrial Development Organisation, *Fertilizer Manual, Development and Transfer of Technology Series No. 13* (United Nations, New York, 1980), pp. 18–31.
2. M. Chou, D. P. Harmon Jr., H. Kahn, S. H. Wittwer, *World Food Prospects and Agricultural Potential* (Praeger, New York, 1977), pp. 1–249; G. O. Barney, Ed., *The Global 2000 Report to the President* (Pergamon, New York, 1981), vol. 1; S. W. Wittwer, in *The Biology of Crop Productivity*, P. S. Carlson, Ed. (Academic Press, New York, 1980), pp. 431–443.
3. Office of Technology Assessment, *Impact of Applied Genetics* (Government Printing Office, Washington, D.C., 1981); I. Rubenstein, B. Gengenbach, R. L. Philips, C. E. Green, *Genetic Improvement of Crops* (Univ. of Minnesota Press, Minneapolis, 1980).
4. A. Pirson and M. H. Zimmermann, *Encyclopedia of Plant Physiology* (Springer-Verlag, Berlin, 1975–1982), vols. 1–11.
5. CHEMRAWN II (Chemical Research Applied to World Needs) is cosponsored by the International Union of Pure and Applied Chemistry (IUPAC) and the International Rice Research Institute (IRRI). Further information is available from the CHEMRAWN II Coordinating Office, International Food Policy Research Institute, 1776 Massachusetts Avenue, NW, Washington, D.C. 20036.
6. L. R. Brown, *The Worldwide Loss of Cropland* (Worldwatch Institute, Washington, D.C., 1978); Centre for Economic and Social Information/Office of Public Information, *United Nations Conference on Desertification* (United Nations, New York, 1978); A. Simantov, *J. Agric. Econ.* **31**, 339 (1980); G. W. Noble, *Agric. Dev. Advis. Serv. Q. Rev.* **36**, 1 (1980); M. Kiley-Worthington, *Food Policy* **5**, 208 (1980).
7. K. Spensley, G. W. Winsor, A. J. Cooper, *Outlook Agric.* **9**, 299 (1978); S. H. Wittwer, in *Global Aspects of Food Production* (Academic Press, New York, in press).
8. D. Pimentel, *CRC Handbook of Pest Management in Agriculture* (CRC Press, Boca Raton, Fla., 1981), vol. 3, pp. 187–588.
9. Ispra Establishment, *Remote Sensing, Application in Agriculture and Hydrology*, G. Fraysse Ed. (Balkema, Rotterdam, 1980), part 1, pp. 3–325.
10. J. K. R. Gasser, *Modelling Nitrogen from Farm Wastes* (Applied Science, Barking, England, 1979); *Effluents from Livestock* (Applied Science, Barking, England, 1980); D. A. Stafford, B. I. Wheatley, D. E. Hughes, *Anaerobic Digestion* (Applied Science, Barking, England, 1980); W. J. Jewell, *Energy, Agriculture and Waste Management* (Ann Arbor Science, Ann Arbor, Mich., 1977), pp. 247–527.
11. See D. Pimentel (*8*), vol. 1, pp. 3–174; R. F. Morris, *Post Harvest Food Losses in Developing Countries* (Board on Science and Technology for International Development, National Research Council, Washington, D.C., 1980).
12. *Planning Guides for the Registration of Pesticides* (Enviro Control Inc., Rockville, Md., from 1981), vols. 1 to 11; P. Dubach, in "The pesticide chemist and modern toxicology," *ACS Symp. Ser. No. 160*, S. K. Bandal, G. J. Marco, L. Goldberg, M. L. Leng, Eds. (American Chemical Society, Washington, D.C., 1981), pp. 513–521.
13. W. Maas, R. van Hes, A. C. Grosscurt, D. H. Deul, in *Chemie der Pflanzenschutz und Schädlingsbekämpfungsmittel*, R. Wegler, Ed. (Springer-Verlag, Berlin, 1981), vol. 6, pp. 424–470.
14. J. J. Menn and C. A. Henrick, in *Crop Protection Chemicals: Directions of Future Development* (Royal Society, London, 1981), pp. 57–71.
15. J. A. A. Renwick, J. P. Vité, H. J. Bestmann, O. Vostrowsky, M. Boness, in *Chemie der Pflanzenschutz und Schädlingsbekämpfungsmittel*, R. Wegler, Ed. (Springer-Verlag, Berlin, 1981), vol. 6, pp. 2–184.
16. H. T. Huang *et al.*, *Biotechnol. Bioeng.* **22**, 1295 (1980); H. J. Phaff, *Sci. Am.* **245**, 76 (September 1981).
17. P. A. Hedin, "Host plant resistance to pests," *ACS Symp. Ser. No. 62* (American Chemical Society, Washington, D.C., 1977), pp. 115–275.
18. Society of Chemical Industry, *Insect Neurobiology and Pesticide Action* (Proceedings of the Society of Chemical Industry Symposium 1979, London, 1980); K. Bauer, D. Berg, E. Bischoff, H. v. Hugo, P. Kraus, in *Chemie der Pflanzenschutz und Schädlingsbekämpfungsmittel*, R. Wegler, Ed. (Springer-Verlag, Berlin, 1981), vol. 6, pp. 216–328.
19. J. Kuć, in *Host-Parasite Interphases*, B. B. Nickol, Ed. (Academic Press, London, 1979), pp. 87–101; P. A. Hedin (*17*), pp. 1–114.
20. H. L. Palm, J. D. Riggleman, D. A. Allison, in *Proceedings of the British Crop Protection Conference*, vol. 1, *Weeds* (British Crop Protection Council, Boots Company Ltd., Nottingham, 1980), pp. 1–6.
21. F. M. Pallos and J. E. Casida, *Chemistry and Action of Herbicide Antidotes* (Academic Press, New York, 1978).
22. A. R. Putman and W. B. Duke, *Annu. Rev. Phytopathol.* **16**, 431 (1978); J. J. Sanders, *Chem. Eng. News* (3 August 1981), p. 20; H. P. Fischer, *Pestic. Sci.*, in press.
23. V. Dittrich, in *Proceedings of the British Crop Protection Conference*, vol. 3, *Pests and Diseases* (British Crop Protection Council, Boots Company Ltd., Nottingham, 1981), pp. 837–846; S. G. Georgopoulos, in *Development of Fungal Resistance to Fungicides*, M. R. Siegel and H. D. Sisler, Eds. (Dekker, New York, 1977), pp. 439–495; D. J. Delp, *Plant Dis.* **64**, 652 (1980).
24. A. F. Kydonieus, *Controlled Release Technologies: Methods, Theory, and Application* (CRC Press, Boca Raton, Fla., 1980), vols. 1 and 2; J. E. Darter *et al.*, *Outlook Agric.* **10**, 318 (1981); I. J. Graham-Bryce and G. S. Hartley, in *Advance of Pesticide Science*, H. Geissbühler, Ed. (Pergamon, Oxford, 1979), part 3, p. 718.
25. C. B. Huffaker and B. A. Croft, *Environ. Health Perspect.* **14**, 167 (1976); L. Brader, *Annu. Rev. Entomol.* **24**, 225 (1979); T. Kommedahl, Ed., *Proceedings of Symposia, IX International Congress of Plant Protection*, vol. 2, *Integrated Plant Protection for Agricultural Crops and Forest Trees, 1979* (Burgess, Minneapolis, Minn., 1981); H. Geissbühler, *Phil. Trans. R. Soc. London Ser. B* **295**, 111 (1981).
26. P. Morgan, *Bot. Gaz.* **141**, 337 (1980); S. H. Wittwer, in *Plant Regulation and World Agriculture*, T. K. Scott, Ed. (Plenum, New York, 1979), pp. 11–33; R. W. F. Hardy, in *ibid.*, pp. 165–206.
27. I. Zelitch, *Chem. Eng. News* (5 February 1979), p. 28; A. Trebst, M. Avron, M. Gibbs, E. Latzko, "Photosynthesis I and II," in *Encyclopedia of Plant Physiology* (Springer-Verlag, Berlin, 1977 and 1979), vols. 5 and 6.
28. J. D. Hesketh and J. W. Jones, *Predicting Photosynthesis for Ecosystem Models* (CRC Press, Boca Raton, Fla., 1980), vol. 1; J. N. Gallagher and P. V. Biscoe, in *Proceedings of a Symposium by BCPC/BPGRG, Opportunities for Chemical Plant Growth Regulators, Monograph No. 21* (British Crop Protection Council, Boots Company Ltd., Nottingham, 1978), p. 113.
29. W. E. Newton, in *Kirk-Othmer Encyclopedia of Chemical Technology* (Wiley, New York, ed. 3, 1981), vol. 15, pp. 942–968; B. J. Miflin, in *The Biology of Crop Productivity*, P. S. Carlson, Ed. (Academic Press, New York, 1980), pp. 255–296; G. W. Colliver, *Farm. Chem.* **143**, 114 (April 1980).
30. G. R. Safir, in *The Biology of Crop Productivity*, P. S. Carlson, Ed. (Academic Press, New York, 1980), pp. 231–252; J. L. Ruehle and D. H. Marx, *Science* **206**, 419 (1979).
31. A. E. Hall, G. H. Cannell, H. W. Lawton, *Agriculture in Semi-Arid Environments* (Springer-Verlag, Berlin, 1979).
32. A. W. Biswas, Ed., *United Nations Water Conference*, part 3, *Water Development, Supply and Management* (Pergamon, Oxford, 1977); K. Shoji, *Sci. Am.* **237**, 62 (November 1977); Z. Solel *et al.*, *Phytopathology* **69**, 1273 (1979).
33. I. K. Vasil, Ed., *Perspectives in Plant Cell and Tissue Culture, Int. Rev. Cytol.*, Suppl. 11B (Academic Press, New York, 1980).
34. W. J. Brill, *Sci. Am.* **245**, 199 (September 1981).
35. The World Bank, *World Development Report 1980* (Oxford Univ. Press, New York, 1980), pp. 46–70.
36. P. Oram, J. Zapata, G. Alibaruho, S. Roy, *Investment and Input Requirements for Accelerating Food Production in Low-Income Countries by 1990* (Research Rep. No. 10, International Food Policy Research Institute, Washington, D.C., 1979), pp. 128–136.
37. J. E. Edmuns, in *Proceedings of Symposia, IX International Congress of Plant Protection*, T. Kommedahl, Ed. (Burgess, Minneapolis, Minn., 1981), vol. 1, pp. 393–397; Food and Agriculture Organization, *Agriculture: Toward 2000* (Food and Agriculture Organization, Rome, 1979), pp. 175–177 and 234; D. J. Greenland, *Science* **190**, 841 (1975); S. Wortman, *ibid.* **209**, 157 (1980).
38. See P. Oram *et al.* (*36*), pp. 88–127; R. Wijewardene, *World Crops* (May/June 1978), p. 128; G. A. Matthews, *Outlook Agric.* **10**, 345 (1981).