Symposium: Assessing the Effects of Agricultural Biotechnology

Assessing the Benefits Associated with Planned Introductions of Genetically Engineered Organisms

Forrest W. Nutter, Jr.

Assistant Professor, Department of Plant Pathology, University of Georgia, Athens 30602. (Current address: Associate Professor, Department of Plant Pathology, 351 Bessey Hall, Iowa State University, Ames, 50011)

Accepted for publication 31 October 1990 (submitted for electronic processing).

Biotechnology is defined by the Congressional Office of Technology Assessment (30) as "any technique that uses living organisms (or parts of organisms) to make or modify products to improve plants or animals, or to develop micro-organisms for specific uses." With the advent of biotechnology, agricultural science is gaining manipulative control of the molecular building blocks of food and fiber production. However, if the use of these blocks by genetic engineers is to have any practical application, then they must be shown to provide a benefit at the whole plant, population, and cropping systems levels. Benefits assessment has been, and will continue to be, an important component of agricultural research.

Benefits assessment in agriculture necessitates estimates of crop production gains and losses resulting from the use of a planned strategy. New disease control strategies involving the use of genetically modified organisms will require proper biological assessment to determine both risks and benefits. Biological assessment data will also be necessary to facilitate agritechnology transfer; that is, to integrate and optimize the beneficial impact of new agricultural biotechnologies on production while at the same time minimizing ecological risk. This symposium, sponsored by the American Phytopathological Society Plant Disease Losses Committee, focuses upon the socioeconomic (8,21), ecological (17), regulatory (19), and scientific (28) assessment of agricultural biotechnology products released into the environment. In my article, I review the question of benefits as it relates to the deployment of genetically engineered organisms.

BENEFITS ASSESSMENT

Proponents of agricultural biotechnology cite numerous benefits that could be obtained from use of genetically engineered organisms (11,31). Production increases are ultimately a function of resource availability and technological advancements (5). Many of the past improvements in agricultural productivity in the United States resulted from low-priced capital inputs such as land, water, fuel, and agrichemicals (14). Since the costs of these inputs are continuing to escalate and/or are causing harm to the environment, there is a need to develop new agricultural technologies that will reduce or eliminate these pitfalls. A proposed technology must satisfy three basic questions. First, does the proposed technology satisfy a need? Second, can the proposed technology be integrated into the current production system without increased environmental risk? Third, is the proposed technology more profitable than the existing technology? Proper biological assessment is necessary to answer each of these questions.

A critical level of information is required before a new technology can be developed and subsequently integrated into a crop production system. Risk management is the process of weighing alternatives to select the most appropriate strategy or action to solve a problem (30). Risk assessment involves the use of scientific data to identify and characterize the magnitudes and probabilities associated with the potential adverse effects that might arise from the introduction and use of a new technology. Risk analysis will require the development and use of sound sampling methods coupled with state of the art methods to track genes, gene segments, and products (11,17,22,23).

The assessment process is said to be "risk driven" (6). Although risk assessment is an important component of the risk management process, risk management should also include an assessment of benefits. The benefits side of the risk management equation is often overshadowed because of the huge emphasis placed upon assessment of risk and public perception of that risk (19,30). As a result, more resources and personnel have been directed toward risk assessment than toward the assessment of benefits (22). However, at least one federal agency (the Environmental Protection Agency) is required by law to "take into account the impact of new products on both production and the agricultural economy" (6). Several regulatory agencies may be charged with weighing the benefits against the risks. Therefore, those who petition to release genetically engineered organisms into the environment must be equally prepared to document the benefits as well as the risks. Demand for benefits data will increase sharply in the next decade as more and more agricultural biotechnologies are developed.

PROBLEM DEFINITION AND SOLUTION

Agricultural production worldwide must continue to increase to meet the ever increasing demand for food and fiber (5,14,26,32). The gap between food production and consumption can be measured by the current status of the world's grain reserves. These are grain surpluses set aside to guard against future shortfalls. World grain reserves have dwindled from 101 days in 1986 to just 54 days at the end of 1988 (32). The world's population is expected to be 39% larger in the year 2000 than it was in 1989. This will require an additional 650 million tons of cereal grains per year (14). Before this global need can be confronted scientifically, there is a practical need to first identify crop production constraints at the national, regional, and farm levels. As world production falls farther behind global demand, the crop losses caused by plant diseases will take on greater and greater importance as constraints to production.

James et al (13) have stated that there are two basic and sequential phases within the context of plant disease control — the definition phase and the solution phase. Accurate estimates of both production and loss are paramount in the definition process since it is "difficult, illogical and inefficient to attempt to solve a problem that has not been adequately defined" (13). Losses incurred by crops due to plant disease have been cited as the primary reason that plant pathology evolved into its own science. Yet, in general, agricultural scientists are not able to provide accurate estimates of direct or indirect crop losses (13,29). Although sound estimates of global losses are difficult to obtain, world figures are cited at about 30–35% preharvest and 10–20% postharvest, as compared to pest-free conditions (26).

Venture capital groups usually demand an analysis of the definition phase before supplying the capital needed to enter into the development (solution) phase. More and more often those involved in crop loss assessment are being called upon to recommend which commodities and which pathosystems within those commodities should be targeted as potential candidates for biotechnology research. This question is difficult to answer because, as stated previously, reliable information concerning crop losses is not generally available. This is also the reason that the definition phase is often lacking in agricultural biotechnology proposals. Research centers involved in planned releases of genetically engineered organisms need to direct part of their resources and personnel to both the definition and benefits phases of research projects.

Development and integration of agricultural biotechnologies into pest management programs embodies the solution process. There are five basic ways (categories) in which agricultural biotechnology products can have a positive impact on crop production. These are: 1) increase the maximum attainable yield of a crop, 2) increase the extensity (area) of a crop, 3) alleviate production constraints (reduce crop losses), 4) decrease the cost of production, and 5) reduce environmental risk.

MAXIMUM ATTAINABLE YIELD

Maximum attainable yield is the yield achieved when the crop is grown under optimum environmental conditions, along with the use of available crop protection tactics when needed. Genetic potential is the primary factor that limits production and not pests or environment. The inverse of the law of the minimum (33) is very much applicable to this situation. When most factors are optimum for crop production, that is, a favorable environment and the lack of abiotic and biotic stresses, then the factor that limits production is the genetic yield potential of the crop. Bringing about an increase in the maximum attainable yield of a crop usually involves the orchestration of many genes that collectively interact to affect growth, radiation interception, and conversion of photosynthate into a harvestable product. The degree to which agricultural biotechnologies might enhance maximum attainable yields or improve quality can be determined using evaluation protocols already in place. Maximum attainable yield trials are often conducted by agronomists, horticulturalists, and plant breeders to evaluate and rank genotypes for genetic yield potential (7,9,34). Similar field trials will be required to document the benefits of new agricultural biotechnologies on the maximum attainable yields of crops. Genetic engineering techniques may better lend themselves to improving the quality of high-yielding genotypes that already will be accepted by growers and consumers.

INCREASING EXTENSITY OF CROP PRODUCTION

An increase in agricultural production can, to a certain extent, be achieved by cultivating more land. Genetic engineering technologies may stabilize production by producing genotypes that yield well across a range of environments—even to the point where a crop can now be produced in an area where it was not previously grown, thus increasing the extensity of crop production. For example, the insertion of a gene for salt tolerance into wheat would enable this crop to be grown on saline soils; or, the insertion of a gene for disease resistance would allow the crop to be grown in an area where a disease was formerly a limiting factor. The American chestnut was an important tree economically and ecologically before it was annihilated in North America by the fungus *Endothia parasitica*. If genetic engineering techniques could be used to eventually produce trees resistant to chestnut blight, then the American chestnut may reestablish itself over its previous geographic range.

There is often a significant genotype × environment interaction for the phenotype yield (7,25). One genotype may produce the highest yield when grown in one environment but may rank well below other genotypes when grown in a different environment. Extending the extensity of production may expose new problems not previously encountered in existing production areas. New crop environments may differ greatly in climate, soil type, and disease populations. New environments can affect pathogen populations directly by providing moisture and temperature conditions more conducive for disease development or indirectly by predisposing the crop to disease attack. Croxall and Smith (5) warn that if a popular new introduction (genetically engineered or otherwise) has a hidden defect that is not revealed before introduction, such as susceptibility to a new pathogen or race, then a large number of producers may suffer a drastic loss in production.

Genetic uniformity in a crop has often been a major contributor to the occurrence of devastating disease epidemics (15). Increased virulence or aggressiveness in the pathogen population coupled with a favorable environment are important factors that contribute to the development of plant disease epidemics. The potato late blight epidemic in 1845 and the coffee rust epidemic in Ceylon in 1870 (and, more recently, in the Americas in 1970) are prime examples of this risk. In 1970, 85% of the corn crop contained Tcms (Texas cytoplasmic male sterility). This germ plasm, coupled with an abundant amount of inoculum of *Helminthosporium maydis* race T inoculum and weather conditions favoring disease development, resulted in approximately 15% of the United States corn crop being destroyed. This represented a loss of 20 million metric tons of corn worth about 1 billion dollars (15).

Most of the new agricultural biotechnologies concern the transfer of the equivalent of single gene traits, for example, herbicide resistance or resistance to specific crop pests and diseases. Tendency of producers to use the most profitable germ plasm is understandable, but it also follows that the genetic base becomes dangerously narrow. Beachy et al (2) have developed transgenic tobacco plants that express the coat protein gene of tobacco mosaic virus (TMV). Plants that expressed the coat protein gene either developed disease symptoms significantly later than control plants or did not develop symptoms. Symptomless plants were found to have a low or undetectable amount of virus. Epidemiological effects of transgenic tobacco plants on TMV epidemics in the field is not known. Since transgenic tobacco plants expressing the coat protein gene can become infected and some virus replication does occur, there may be a danger of TMV-resistant strains developing. Level of coat protein expression in transgenic tobacco plants to alfalfa mosaic virus was found to be dependent upon leaf age (18). The greatest concentration of coat protein was found in young expanding leaves, whereas coat protein was often not detected in older leaves located more than 10 nodes from the apical meristem. Several epidemiological questions remain unanswered, such as what proportion of tobacco leaves in a field must express coat protein to effectively prevent plant disease epidemics and what level of coat protein expression is needed to obtain a delay in the time to reach a critical level of disease incidence? Disease control and yield benefits of genetically engineered plant populations need to be determined, as well as the risks associated with genetic uniformity. Benefits assessment in contained facilities at the whole plant level may not provide an accurate measure of the effects of genetically engineered organisms interacting with other organisms at the population level in the field. Field testing over a range of environments can provide important information concerning the performance and stability of bioengineered plants and organisms at the population level (7,25). Properly designed field tests can help us to better understand treatment (genetically engineered organisms) by environment interactions to facilitate the transfer of new agritechnologies to farm environments, where they will be most effective (25).

ALLEVIATE PRODUCTION CONSTRAINTS

Although agricultural production may be increased genetically by raising the maximum attainable yield or by increasing the geographic area where a crop can be produced, in many instances agricultural pests continue to be a limiting factor to raising the yield obtained by farmers. Plant pathologists will continue to have a major role in alleviating production constraints; therefore, information concerning the prevalence of plant pathogens and the losses they cause is needed to identify and prioritize crop production conditions.

To help clarify disease control objectives, several terms concerning different levels of yield potential need to be defined (35) or redefined. Attainable yield is the yield obtained at a specific location when all available crop protection tactics are used to alleviate biotic stress. Production systems that optimize attainable yields may not be the most desirable systems economically or environmentally. Cost of deploying all available control tactics to achieve attainable yield may be higher than the return expected from the sale of the crop and may result in greater harm to the environment due to excessive inputs. In contrast, economic yield is the achievable yield that provides the highest net return on expenditure. If the cost of utilizing genetically engineered organisms for plant disease control exceeds the expected return, the technology is not likely to be adopted. Actual yield is the production level achieved when producers utilize the disease control measures currently recommended for a crop or cropping system, yet several weeds, diseases, and insects still limit yield. Primitive yield is the yield obtained without deploying any disease control tactics.

Agricultural biotechnologies may have their greatest impact on increasing agricultural production by closing the gap between actual yield and attainable yield; i.e. by reducing crop losses. The difference between actual and attainable yield is the method used by FAO to report actual losses (35). This loss estimate corresponds to the unavoidable losses caused by plant pests and pathogens, which, if alleviated, would allow plant genotypes to realize yields closer to attainable yield. The difference between attainable and actual yield may actually increase when the maximum attainable yield is increased, since the demand for photosynthate will be increased (10).

The difference between actual yield and attainable yield is the figure that researchers should use as their justification (definition phase) for undertaking new agricultural biotechnology projects. All too often researchers cite the difference between primitive and actual yield or the difference between primitive and attainable yield as the figure representing the loss for a given crop. Such figures are misleading since the difference between primitive yield and actual yield already represents the benefits obtained from currently used pest control programs. Likewise, reporting yield losses as the difference between primitive yield and attainable yield ignores past disease control achievements resulting in an overestimation of the loss actually incurred by farmers. When yield losses are overestimated, then the benefits to be derived from the deployment of any new disease control tactic (including biotechnology-based products) will also be overestimated.

Although information on crop loss is an essential part of the definition process, there is an important question concerning agritechnology transfer that surfaces after the solution phase is completed: "Is the use of the proposed technology more profitable than the existing technology?" The ability of agricultural scientists to accurately and precisely measure yield increases brought about by the proposed release of genetically engineered organisms is often taken for granted. As stated earlier, the lion's share of attention has been centered upon the assessment of risks while the scientific community that is available to document "benefits" has received considerably less attention and support. There is, and will continue to be, a pressing need to obtain accurate and credible scientific information to document the benefits realized from the use of agricultural biotechnologies. Benefits of new technologies must be measured in terms of efficacy of control and improvements in yield and/or quality over the currently used technology. With regard to the use of agricultural biotechnologies in plant pathology, this requires accurate and precise methods of disease assessment and quantitative information concerning the relationship between disease intensity and yield (29).

Disease intensity-yield loss models. Models are often used to quantify the relationship between disease intensity and yield (13,29,37). Once this relationship is quantified, economic thresholds based on disease intensity can be developed and used as a means to project yield and profit gains from a proposed biotechnology. Often these same models can also be employed to evaluate these technologies once they reach the field testing stage. In general, three types of models can be used as tools to quantify the effect of new biotechnologies on disease intensity and yield (3,29,37). These are critical (single) point, multiple point, and area under the disease progress curve (AUDPC) models. The critical point model involves assessing disease intensity at a growth stage found to have the best relationship to yield loss. Critical point models use a single independent variable to estimate loss. For long season crops, yield may be significantly reduced when plants are attacked at several growth stages during the season. Multiple point models, in which disease intensity is assessed several times during the cropping season, can account for the effects of disease on yield for long season epidemics. The AUDPC model involves plotting disease intensity with respect to time and determining the area under the resultant curve. Several computer programs have been developed to calculate AUDPC values (3). An advantage of the AUDPC model is that this model can be used to quantify epidemics that are not continuous in nature.

The paired plot technique is a method that has often been used by plant pathologists to determine the efficacy of a new disease control tactic. Such experiments normally consist of a nontreated control plot that is planted adjacent to a plot receiving the new disease control technology. Although such studies often provide useful information concerning the disease control potential of the new technology in terms of adoption by growers, there are several drawbacks associated with this technique. First, there is the hazard of interplot interference (37), and second, the difference in yield between treated and nontreated plots is often analogous to the difference between attainable and primitive yield, which ignores the yield improvements made from disease control tactics currently used by growers. To measure the true economic benefit associated with the use of a new technology, a measure of attainable yield must be included. This may require the inclusion of one or more treatments. Third, in paired plot studies, the pathogen is often introduced to both treated and nontreated plots, which may greatly overestimate the benefits that a grower would realize from using the same technology. For example, in several test protocols involving virus resistant transgenic vs. nontransgenic (susceptible) plants, all plants are inoculated at one point in time and the incidence of infection and yield are then determined. Rarely in nature would an epidemic result in all plants being infected at the same point in time. Noninfected plants and plants infected later in the growing season often compensate for plants infected early in the season. This form of yield compensation at the population level, which helps to narrow the gap between attainable and primitive yield, is left unaccounted for when entire populations are inoculated at one point in time. Spatial patterns of disease on yield compensation should also be considered (12).

Simulation approaches. Once the relationship between disease intensity and yield loss has been sufficiently quantified, estimates of benefits as a result of employing a new agricultural biotechnology can be made for several scales of extensity (county, state, region, commodity, etc.). Climatic data bases can be used to identify geographic areas favorable for disease development (4,36). This information, coupled with data on the geographic distribution of pathogens and pests (pathogen zoning), may allow estimation of the potential economic benefits to be derived from the use of new agricultural biotechnologies (27). Unfortunately, pathogen zoning data bases are rarely available or accessible to allow epidemiologists to make impact estimates using simulation and modeling approaches. The best example to date of how useful these approaches can be is a study conducted by Andow et al (1) to estimate the potential benefits from using non-ice-nucleating bacteria to reduce frost damage to potato in the United States. Frequency distributions of first frosts in spring and fall were determined for four production sites and coupled with a model simulating potato growth. Potential damage from frost was determined at these sites using three simulated planting dates, and cost-benefit ratios were determined.

Another approach to estimating benefits would be to establish a crop loss assessment information and retrieval network whereby data bases concerning crop losses caused by particular pests could be stored and categorized (20) to generate crop loss maps. Zadoks and Rijsdijk (36) generated crop loss maps for cereal diseases and pests of Europe using climatic and pest occurrence data collected over a 10-yr period. Where sufficient data were available, "isodams," which are isolines drawn for a particular level of crop loss (expressed as a percentage of attainable yield), were included. For example, isodam lines for losses in wheat caused by powdery mildew (*Erysiphe graminis*) indicated 10–20% loss of attainable yield for most areas in continental Europe, although there were some areas identified where losses were as high as 60%. Isodam maps, coupled with simulation models, could be used as a means to estimate the potential benefits of new agricultural biotechnologies.

DECREASE COST OF PRODUCTION

Application of genetic engineering techniques initially developed with model biological systems most likely will find application in agricultural production systems where there is a profit motive to develop them. Agricultural production systems in which losses caused by diseases are well documented may be among the first to receive research funding for agritechnology transfer. The total cost of plant diseases is the amount of crop loss occurring despite the use of disease control tactics, plus the total cost for employing these control tactics. The permissible degree of risk varies with the extent and price of the crop. If the potential returns are high, then greater risks may be acceptable. Some plant diseases can be controlled almost entirely by one or more methods, and therefore, the only financial losses are those associated with the cost of control. This is the situation with late leaf spot of peanut, caused by *Cercosporidium personatum*. On the average, 7-8 fungicide applications are applied to the peanut crop each season in Georgia to control this disease. This costs Georgia producers more than 30 million dollars in fungicide costs alone each season (24). Agricultural biotechnology products will first be developed for pathosystems, where the profit motive is high and there is high probability that the desired technology can be achieved. Although the profit motive is high enough to justify an attempt to develop leafspot resistant varieties via genetic engineering technology, little is known about the peanut genome compared to other crops such as corn, wheat, and tobacco. Although resistance has been found in some wild species of peanut, transformation and regeneration techniques for peanuts have not been developed. Therefore, even when the profit motive is high, the current level of knowledge may be insufficient to immediately apply genetic engineering techniques to other production systems. Conversely, Klopperburg (16) points out that there may be a number of opportunities for the production of socially and ecologically valuable agricultural biotechnology products that may never be pursued because they would not prove to be profitable. Determining the reduction or increase in the cost of production associated with the use of agricultural biotechnology products will be an important component of benefits assessment. While new technologies may initially offer a means of reducing costs, net profits of farm producers often wither as more producers adopt a new technology (16,27,31).

REDUCED ENVIRONMENTAL RISK

Agricultural biotechnologies are expected to result in less reliance on pesticides for plant protection. Genetically engineered plants (resistance) and microorganisms (biocontrol agents) should reduce the risk of pesticide contamination of crops, soils, and water. Benefits derived from the use of biotechnologies that reduce the amount of pesticide released into the environment can be documented by obtaining baseline measurements of pesticide residues in crops, soils, and water and comparing these with pesticide levels measured after the introduction of the new technology. Through surveys and pesticide sales records, the reduction in the amount of pesticide being introduced into farm environments can also be determined. Indirect evidence for reduced environmental risks may be obtained from ongoing wildlife biology studies and from geographic and temporal data bases supplied by the Center for Disease Control in Atlanta. For example, documented increases in the populations of several predatory bird species have been associated with the banning of DDT.

Tools of genetic engineering not only allow for the transfer of new sources of resistance to diseases and pests, but multiple copies of genes can now be introduced to greatly increase the amount of gene product. A new question is now being raised: Is there a risk of ingesting virus coat protein from the fruit of transgenic plants or increased levels of BT (*Bacillus thuringiensis*) toxin to control insects? Zehr (38) expressed concern that the inherent safety of these compounds, which are meant to replace pesticides, is largely undetermined.

CONCLUSION

The socioeconomic and ecological benefits derived from the use of new agricultural biotechnologies need to be identified and weighed against the benefits obtained from the agricultural technologies they are meant to replace. Field testing has several important advantages over testing only in controlled environments. First, it can help us avoid the adoption of biotechnologies that perform extremely well in controlled environments but perform poorly when employed in real farm situations. Second, field testing may help researchers to avoid rejecting biotechnologies that may be effective in environments other than those tested under controlled conditions. Biological assessment systems used to evaluate pesticides, breeding lines, and disease control tactics are already in place and can be used as model systems to develop appropriate methods to assess the benefits achieved through the planned releases of genetically engineered organisms. There remains, however, a lack of reliable crop loss assessment information, which is needed in the definition, solution, and postsolution phases of agricultural research. Federal, state, and industry programs should not opt to support agricultural biotechnology programs in the short term at the expense of quantitative biological assessment programs that will eventually be needed in the long term to assess benefits and risks and to efficiently integrate new agricultural biotechnologies into crop production systems.

LITERATURE CITED

1. Andow, D. A., Teng, P. S., Johnson, K. B., and Snapp, S. S. 1989. Simulating the effects of bioengineered non-ice nucleating bacteria on potato yields. Agric. Systems 29:81-92.
2. Beachy, R. N., Abel, P. P., Nelson, R. S., Rogers, S. G., and Fraley, R. T. 1987. Transgenic plants that express the coat protein gene of TMV are resistant to infection by TMV. Pages 205-213 in: Molecular Strategies for Crop Protection, C. J. Arntzen and C. Ryan, eds. UCLA Symposia on Molecular and Cellular Biology, New Series, Alan R. Liss, Inc., New York. 443 pp.
3. Berger, R. D. 1988. The analysis of the effects of control measures on the development of epidemics. Pages 138-151 in: Experimental Techniques in Plant Disease Epidemiology. Springer-Verlag, New York. 299 pp.
4. Coakley, S. M. 1988. Variation in climate and prediction of disease in plants. Annu. Rev. Phytopathol. 26:163-181.
5. Croxall, H. E., and Smith, L. P. 1984. The Fight for Food: Factors Limiting Agricultural Production. George Allen and Unwin, London. 167 pp.
6. Curtis, C. R. 1988. Agricultural Benefits Derived from Pesticide Use: A Study of the Assessment Process. The Ohio State University, Columbus. 148 pp.
7. Eberhart, S. A., and Russell, W. A. 1966. Stability parameters for comparing varieties. Crop Sci. 6:36-40.
8. Fulkerson, J. F. 1991. Understanding the impacts of biotechnology. Phytopathology 81:343.
9. Garcia, P., Offutt, S. E., and Sonka, S. T. 1988. Assessing agricultural research strategies. J. Prod. Agric. 1:287-292.
10. Gaunt, R. E. 1980. Physiological basis of yield loss. Pages 98-111 in: Crop Loss Assessment, P. S. Teng and S. V. Krupa, eds. Proceedings of E. C. Stakman Commemorative Symposium. Agric. Exp. Stn. Misc. Publ. F-1980. University of Minnesota, Minneapolis.
11. Hedin, P. A., Menn, J. J., and Hollingworth, R. M., eds. 1988. Biotechnology for Crop Protection. American Chemical Society, Washington, D.C. 471 pp.
12. Hughes, G. 1990. Characterizing crop responses to patchy pathogen attack. Plant Pathol. 39:2-4.
13. James, W. C., Teng, P. S., and Nutter, F. W., Jr. 1990. Estimated losses of crops from plant pathogens. Pages 15-51 in: CRC Handbook of Pest Management, 2nd Ed. D. Pimentel, ed. 765 pp.
14. Joint Council on Food and Agricultural Sciences. 1984. Summary: Needs Assessment for the Food and Agricultural Sciences. Report to the Congress from the Secretary of Agriculture, January 1984. Department of Agriculture, Washington, D.C. 76 pp.

15. Klinkowski, M. 1970. Catastrophic plant diseases. Annu. Rev. Phytopathol. 8:37-60.
16. Kloppenburg, J. R., Jr. 1988. First the Seed. Cambridge University Press, Cambridge. 349 pp.
17. Kluepfel, D. A., Kline, E. L., Skipper, H. D., Hughes, T. A., Gooden, D. T., Drahos, D. J., Barry, G. F., Hemming, B. C., and Brandt, E. J. 1991. The release and tracking of genetically engineered bacteria in the environment. Phytopathology 81:348-352.
18. Loesch-Fries, L. S., Halk, E., Merlo, D., Jarvis, N., Nelson, S., Krahn, K., and Burhop, L. Expression of alfalfa mosaic virus coat protein gene and anti-sense cDNA in transformed tobacco tissue. Pages 221-234 in: Molecular Strategies for Crop Protection. C. J. Arntzen and C. Ryan, eds. UCLA Symposia on Molecular and Cellular Biology Series. Alan R. Liss, Inc. New York. 443 pp.
19. MacKenzie, D. R. 1991. The national biological impact assessment program. Phytopathology 81:361.
20. Main, C. E., and Bryne, S. V. 1985. Estimates of Crop Losses in North Carolina due to Plant Diseases and Nematodes. Department of Plant Pathology Special Publication 5, North Carolina State University, Raleigh. 183 pp.
21. Martin, M. A. 1991. Socioeconomic aspects of agricultural biotechnology. Phytopathology 81:356-360.
22. National Academy of Sciences. 1989. Field Testing Genetically Modified Organisms: Framework for Decisions. National Academy Press, Washington, D.C. 170 pp.
23. National Academy of Sciences. 1989. The Ecology of Plant-Associated Microorganisms. National Academy Press, Washington, D.C. 34 pp.
24. Nutter, F. W., Jr., Littrel, R. H., and Brenneman, T. B. 1990. Evaluation of fungicide efficacy to control late leafspot in peanut using a multispectral radiometer. Phytopathology 80:102-108.
25. Roseille, A. A., and Hamblin, J. 1981. Theoretical aspects of selection for yield in stress and non-stress environments. Crop Sci. 21:943-946.
26. Smith, I. M., Chiarappa, L., and Van der Graaff, N. A. 1984. World crop losses: An overview. Pages 213-223 in: Plant Diseases: Infection, Damage and Loss. R. K. S. Wood and G. J. Jellis, eds. Blackwell Scientific Publications, Oxford, England. 327 pp.
27. Tauer, L. W., and Love, J. 1989. The potential economic impact of herbicide-resistant corn in the USA. J. Prod. Agric. 2:202-207.
28. Teng, P. S. 1991. Assessing the potential impact of planned releases of bioengineered organisms using modeling and non-modeling approaches. Phytopathology 81:353-356.
29. Teng, P. S., and Johnson, K. B. 1988. Analysis of epidemiological components in yield loss assessment. Pages 179-189 in: Experimental Techniques in Plant Disease Epidemiology. Springer-Verlag, New York. 299 pp.
30. U.S. Congress, Office of Technology Assessment. 1988. New Developments in Biotechnology, Field-Testing engineered Organisms: Genetic and Ecological Issue. OTA-BH-350, May 1988. U.S. Government Printing Office, Washington D.C. 150 pp.
31. U.S. Congress, Office of Technology Assessment. 1988. New Developments in Biotechnology, U.S. Investment in Biotechnology. OTA-BA-360. U.S. Government Printing Office, Washington, D.C. 296 pp.
32. U.S. Department of Agriculture. 1989. World Agriculture Situation and Outlook Report. U.S. Dep. Agric. Economic Research Service Report, WAS-55. Washington, D.C. 79 pp.
33. Waggoner, P. E., Norvell, W. A., and Royle, D. J. 1980. The law of the minimum and the relation between pathogen, weather, and disease. Phytopathology 70:59-64.
34. Waibel, H. 1986. The Economics of Integrated Pest Control in Irrigated Rice. Crop Production Monographs. Springer-Verlag, New York. 196 pp.
35. Zadoks, J. C. 1981. Crop loss today, profit tomorrow: An approach to quantifying production constraints and measuring progress. Pages 5-11 in: Crop Loss Assessment Methods. FAO Manual on the Evaluation and Prevention of Losses by Pests, Diseases, and Weeds. L. Chiarappa, ed. Commonwealth Agricultural Bureaux, Farnham Royal.
36. Zadoks, J. C., and Rijsdijk, F. H. 1984. Atlas of Cereal Diseases and Pests in Europe, Vol. III. PUDOC, Wageningen, Netherlands. 169 pp.
37. Zadoks, J. C., and Schein, R. D. 1979. Epidemiology and Plant Disease Management. Oxford University Press, New York. 427 pp.
38. Zehr, E. I. 1989. Reflections in plant disease control. Plant Dis. 73:372.