

Final Scientific/Technical Report

DOE Award Number: DE-FG02-95ER20194
Project Title: Corn Storage Protein - A Molecular Genetic Model
Project Principal Investigator: Joachim Messing
Recipient Organization: Rutgers, The State University of New Jersey

Executive Summary

Corn is the highest yielding crop on earth and probably the most valuable agricultural product of the United States. Because it converts sun energy through photosynthesis into starch and proteins, we addressed energy savings by focusing on protein quality. People and animals require essential amino acids derived from the digestion of proteins. If proteins are relatively low in certain essential amino acids, the crop becomes nutritionally defective and has to be supplemented. Such deficiency affects meat and fish production and countries where corn is a staple. Because corn seed proteins have relatively low levels of lysine and methionine, a diet has to be supplemented with soybeans for the missing lysine and with chemically synthesized methionine. We therefore have studied genes expressed during maize seed development and their chromosomal organization.

A critical technical requirement for the understanding of the molecular structure of genes and their positional information was DNA sequencing. Because of the length of sequences, DNA sequencing methods themselves were insufficient for this type of analysis. We therefore developed the so-called "DNA shotgun sequencing" strategy, where overlapping DNA fragments were sequenced in parallel and used to reconstruct large DNA molecules via overlaps. Our publications became the most frequently cited ones during the decade of 1981-1990 and former Associate Director of Science for the Office of Basic Energy Sciences Patricia M. Dehmer presented our work as one of the great successes of this program.

A major component of the sequencing strategy was the development of bacterial strains and vectors, which were also used to develop the first biotechnology crops. These crops possessed new traits thanks to the expression of foreign genes in plants. To enable such expression, chimeric genes had to be constructed using our materials and methods by the industry. Because we made our materials and methods freely available to academia and industry, progress in plant research and new crop development could accelerate and benefit the public.

This impact is best documented by me receiving the Wolf Prize in Agriculture "for innovations in recombinant DNA cloning, which revolutionized agriculture, and for deciphering the genetic codes of crop plants."

Comparison of the actual accomplishments with the objectives of the project

We began our analysis with publishing the first amino acid sequence of a plant storage protein. With progress in DNA sequencing and computational methods and the advantage of maize genetics, we were able to achieve our objectives to characterize the gene family encoding maize seed storage proteins, transposable elements in maize, epigenetic regulation of genes, and creating a high-methionine transgenic maize line. We also used RNA interference to stably increase the lysine content in the seed in a dominant fashion. Many of these accomplishments exceeded the original objectives because of the serendipity of research. Without these unexpected results, there would be no discovery. It is clear that the small amount of money provided from this program could not have been sufficient to achieve these results, unless we received additional support from NIH, NSF, and institutional resources. In particular, the Plant Genome Program of NSF was substantial. However, the publications in this report cover only DOE funded work (126) and the ones from the Plant Genome Initiative Research (PGIR) were not included.

Project summary for the entire period

This project has been continuously funded from 1981 to 2009 with less than \$100K in direct cost per year with 10 renewal applications for 3 or fewer years of funding. During this period we had achieved a complete understanding of the prolamin genes in maize and their organization in the genome. We found that haplotypes differ in gene copy number and expression of different copies. We also could insert a cluster of sorghum storage protein genes into maize by stably inserting an intact 45 kb chromosomal fragment into the maize genome, demonstrating the conservation of gene regulation between these species. As the genome had expanded due to transposable elements, we had characterized their structures and positions in the genomes and their contribution to allelic variation. Taking advantage of seed pigmentation as a reporter system, we had isolated an epiallele of a transcription factor, providing us with a new system of paramutation. We identified the second case of genomic imprinting in plants, affecting the methionine content in seeds. We received one patent for a high-methionine variant of corn and published textbooks on recombinant DNA techniques and methods in plant molecular biology.

Details of our results are presented in our publications below with 4.5 papers per year over 28 years, accounting for our productivity during the funding period. I also list patents, textbooks, abstracts, invited lectures, and seminars, where our results have been presented.

Publications (126)

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- Snustad, D.P., Hunsperger, J., Chereskin, B.M., and Messing, J. 1986. Isolation and characterization of a maize glutamine synthetase cDNA and its utilization in studies of the molecular basis of methionine sulfoximine resistance in black Mexican sweet cell culture lines. Sixth International Congress of Plant Tissue and Cell Culture, Minneapolis, Minnesota.
- Messing, J., Das, P., and Kirihara, J. 1986. Molecular architecture of plant genes. First International Symposium on Chromatin Structure of Plant Genes, Frankfurt, West Germany.
- Messing, J. 1986. Why do zein genes have no introns? EMBO Workshop on Plant Storage Protein Genes, Freiburg, West Germany.
- Messing, J. 1986. Advances in molecular biology techniques and their use in probing gene structure and function. Mid-America Molecular Biology Colloquium, Afton, Oklahoma.
- Messing, J. 1987. The use of M13 in molecular biology. XIV International Botanical Congress, West Berlin.
- Messing, J. 1987. The manipulation of zein genes to improve the nutritional value of corn. Annual DNA Plant Technology Corporation Scientific Advisory Board Conference, Philadelphia, PA.
- Messing, J. 1987. The use of M13 in molecular biology. The Lake Tahoe Symposium: Advances in Recombinant DNA Technology, Lake Tahoe, Nevada.
- Kirihara, J., Das, O.P. and Messing, J. 1988. Allelic variations that control storage protein synthesis. Third Chemical Congress of North America. Toronto, Canada.
- Messing, J. 1988. The use of M13 in molecular biology. 14th International Congress of Biochemistry, Prague, Czechoslovakia.
- Messing, J. 1989. The use of M13 in molecular biology. Workshop on Trends in Comparative Molecular Genetics, Liblice, Czechoslovakia.
- Benner, M., Das, P., and Messing, J. 1990. Maize stocks exhibiting high frequency of recombination: cytological analysis. Maize Genetics Meeting, Delavan, WI.
- Cruz-Alvarez, M., Chaudhuri, S., and Messing, J. 1990. Molecular analysis of a high methionine variant of maize. Maize Genetics Meeting, Delavan, WI.
- Das, P., Levi-Minzi, S., Fossella, J., Benner, M., and Messing, J. 1990. Maize stocks exhibiting high frequency of recombination: molecular and phenotypic analysis. Maize Genetics Meeting, Delavan, WI.
- Messing, J. 1990. Somatic recombination in maize. A new pathway for genetic diversity? 20th Meeting of the Federation of European Biochemical Societies, Budapest, Hungary.
- Timmermans, M. and Messing, J. 1991. A gemini virus-derived shuttle vector for maize. Maize Genetics Meeting, Delavan, WI.
- Ueda, T. and Messing, J. 1991. A homologous expression system for cloned zein genes. Maize Genetics Meeting, Delavan, WI.
- Chaudhuri, S. and Messing, J. 1991. Physical mapping of Zpr10/22, a regulatory locus controlling the expression of methionine-rich 10kD zein. Maize Genetics Meeting, Delavan, WI.
- Wu, L., Ueda, T. and Messing, J. 1991. Terminator function of 3' flanking region in maize 27 kD zein genes. Maize Genetics Meeting, Delavan, WI.
- Schickler, H., Cruz-Alvarez, M. and Messing, J. 1991. Regulation of high methionine 10kD zein production in Mo17. Maize Genetics Meeting, Delavan, WI.
- Das, O.P. and Messing, J. 1991. Novel genome rearrangements in maize. Maize Genetics Meeting, Delavan, WI.
- Das, O.P. and Messing, J. 1991. Novel genome rearrangements in maize. Keystone Symposium on Plant Molecular Biology, Keystone, CO.

- Chaudhuri, S., Benner, M.S. and Messing, J. 1992. Genetic analysis of a zein gene regulator. Maize Genetics Meeting, Pacific Grove, CA.
- Das, O.P. and Messing, J. 1992. A novel allele of the *P* locus that conditions patterned pericarp. Maize Genetics Meeting, Pacific Grove, CA.
- Hu, W., Das, O.P. and Messing, J. 1992. DNA rearrangement of 27 kD zein genes involving an insertion element. Maize Genetics Meeting, Pacific Grove, CA.
- Timmermans, M.C.P., Das, O.P. and Messing, J. 1992. Identification of *cis* and *trans* functions needed for wheat dwarf virus replication. Maize Genetics Meeting, Pacific Grove, CA.
- Ueda, T., Schmidt, R. and Messing, J. 1992. Sequence-specific *trans*-activation of zein promoters by *opaque-2* in maize protoplasts. Maize Genetics Meeting, Pacific Grove, CA.
- Wu, L., Ueda, T. and Messing, J. 1992. 3' processing of a maize 27 kDa zein mRNA. Maize Genetics Meeting, Pacific Grove, CA.
- Ueda, T., Wang, Z., and Messing, J. 1993. Identification of a transcriptional activator element in the 27-kDa zein promoter, the -300 element. Maize Genetics Meeting, St. Charles, IL.
- Swarup, S. and Messing, J. 1993. A novel high-methionine zein gene. Maize Genetics Meeting, St. Charles, IL.
- Das, O.P. and Messing, J. 1993. Properties of a hypermethylated *P* allele. Maize Genetics Meeting, St. Charles, IL.
- Wu, L., Ueda, T., and Messing, J. 1993. 3' processing of the maize 27-kDa zein mRNA. Maize Genetics Meeting, St. Charles, IL.
- Chaudhuri, S. and Messing, J. 1993. Imprinting of a zein post-transcriptional regulator. Maize Genetics Meeting, St. Charles, IL.
- Timmermans, M.C.P., Das, O.P., Benner, M.S., and Messing, J. 1993. A maize stock exhibiting increased recombination. Maize Genetics Meeting, St. Charles, IL.
- Chaudhuri, S. and Messing, J. 1993. Allele-specific parental imprinting of a post-transcriptional gene regulator in maize. Gordon Conference, Wolfeboro, NH.
- Das, O.P. and Messing, J. 1993. An epigenetic mechanism for variegation in maize. Gordon Conference, Wolfeboro, NH.
- Timmermans, M.C.P., Das, O.P., and Messing, J. 1993. A maize stock exhibiting increased recombination. Gordon Conference, Wolfeboro, NH.
- Chaudhuri, S. and Messing, J. 1993. Allele-specific parental imprinting of a post-transcriptional regulator in maize. American Society for Biochemistry and Molecular Biology Fall Symposium, Keystone, CO.
- Hu, W., Das, O.P. and Messing, J. 1994. *Zeon-1*, a member of an active retrotransposon family in maize. Maize Genetics Meeting, St. Charles, IL.
- Lund, G., Das, O.P. and Messing, J. 1994. Chromatin structural differences between the *P-rr* allele and the hypermethylated *P-pr* allele of the *P*-locus. Maize Genetics Meeting, St. Charles, IL.
- Ueda, T., Wang, Z., Pham, N. and Messing, J. 1994. Identification of a transcriptional activator-binding element in the 27-kDa zein promoter, the -300 element. Maize Genetics Meeting, St. Charles, IL.
- Das, O.P., Timmermans, M. and Messing, J. 1994. A maize stock exhibiting increased recombination. Maize Genetics Meeting, St. Charles, IL.
- Messing, J. 1995. Regulation of gene silencing during plant reproduction and development. Japan-U.S.A. Workshop on Modification of Gene Expression and Non-Mendelian Inheritance, Tsukuba, Japan.
- Timmermans, M., Das, P. and Messing, J. 1995. Molecular characterization of an unselected crossover. Maize Genetics Meeting, Pacific Grove, CA.
- Ueda, T., Wang, Z. and Messing, J. 1995. The highly conserved -300 element in the zein promoters serves as the binding site for a transcriptional activator, PBF, and

- modulates a high level of transcriptional activity. Maize Genetics Meeting, Pacific Grove, CA.
- Bradeen, J., Timmermans, M. and Messing, J. 1996. Are P-locus epiallele methylation status and phenotype set during inflorescence of embryo development by maternal influence? Maize Genetics Meeting, St. Charles, IL.
- Llaca, V. and Messing, J. 1996. Positional cloning of *dzrl*: Physical analysis of the 22-kDa α -Zein cluster region in *Zea mays* L. Maize Genetics Meeting, St. Charles, IL.
- Goettel, W. and Messing, J. 1996. Molecular characterization of an *En/Spm*-like transposable element in *Zea mays* L. Maize Genetics Meeting, St. Charles, IL.
- Llaca, V., Wing, R. and Messing, J. 1997. Sorghum-maize microsynteny of the 22-kDa α -zein cluster region. Maize Genetics Meeting, Clearwater Beach, FL.
- Matvienko, M. and Messing, J. 1997. Violation of the DNA constancy rule in plant development. Maize Genetics Meeting, Clearwater Beach, FL.
- Wang, Z., Ueda, T. and Messing, J. 1997. Characterization of the prolamin-box binding factor (PBF) and its role in the regulation of 27 kDa zein gene. Maize Genetics Meeting, Clearwater Beach, FL.
- Llaca, V. and Messing, J. 1998. Comparative genome analysis of the 22kDa alpha-zein cluster region in *Zea mays*, *Sorghum bicolor* and *Oryza sativa*. Maize Genetics Meeting, Lake Geneva, WI.
- Llaca, V., Song, R. and Messing, J. 1999. DNA sequence analysis of a gene-dense region of *Zea Mays*. Plant Animal Genome VII Conference, San Diego, CA.
- Lai, J. and Messing, J. 1999. Eliminating genetic variability of the high methionine phenotype in maize. Maize Genetics Meeting, Lake Geneva, WI.
- Goettel, W., Das, O.P. and Messing, J. 1999. *PI-rr* is paramutable when heterozygous with the paramutagenic *PI-pr* allele. Maize Genetics Meeting, Lake Geneva, WI.
- Lai, J. and Messing, J. 2000. Stable expression of the high methionine storage protein gene in transgenic progenies of various maize inbred lines. Maize Genetics Meeting, Coeur d'Alene, ID.
- Goettel, W. and Messing, J. 2000. Heritable allelic interaction between *P-pr* and *P-rr*. Maize Genetics Meeting, Coeur d'Alene, ID.
- Song, R., Llaca, V. and Messing, J. 2001. Sequencing of a 350-kilobase region of maize chromosome 4S encompassing the 22-kDa α -zein gene subfamily. Plant and Animal Genome IX Conference, San Diego, CA.
- Goettel, W. and Messing, J. 2001. Paramutation of the *p1* locus in maize. Maize Genetics Meeting, Lake Geneva, WI.
- Song, R., Llaca, V. and Messing, J. 2001. Sequencing of a 350-kilobase region of maize chromosome 4S encompassing the 22-kDa α -zein gene subfamily. Maize Genetics Meeting, Lake Geneva, WI.
- Segal, G., Ward, K. and Messing, J. 2001. Expression of reporter genes in transgenic maize. Maize Genetics Meeting, Lake Geneva, WI.
- Song, R. and Messing, J. 2002. Characterization of the maize 19 kDa α zein gene families. Plant and Animal Genome X Conference, San Diego, CA.
- Goettel, W. and Messing, J. 2002. Paramutagenicity of the *p1* locus is correlated with enhancer element copy number. Maize Genetics Meeting, Orlando, FL.
- Segal, G., Song, R. and Messing, J. 2002. Expression of α -zein promoters in transgenic maize. Maize Genetics Meeting, Orlando, FL.
- Song, R., Messing, J. 2003. Genomic regions comprising the entire alpha zein gene family of *Zea mays* in a single inbred line. 45th Annual Maize Genetics Conference, Lake Geneva, Wisconsin.
- Song, R., Messing, J. 2003. Haplotypes of a genomic region containing *z1C* gene family in maize. 45th Annual Maize Genetics Conference, Lake Geneva, Wisconsin.
- Messing, J., Song, R. 2004. Genomic anatomy of a large storage protein gene family in corn, 9th International Symposium on Plant Seeds, Gatersleben, Germany.

- Goettel, Wolfgang, Messing, J. 2006. Allelic diversity of the p locus by changes and replacements of regulator sequences, Maize Genetics Conference, Pacific Grove, CA.
- Miclaus, M., Messing, J. 2006. Sequence analysis of the alpha-zein gene family in two maize inbred lines, Maize Genetics Conference, Pacific Grove, CA.
- Goettel, W., Messing, J. 2006. Evolution of the Complex *Pl-wr* Cluster in Maize, Plant and Animal Genome XV, San Diego, CA.
- Miclaus, M., Messing, J. 2007. Haplotype variation of 19 kDa alpha-zein gene loci, Maize Genetics Conference, St. Charles, Illinois.
- Messing, J. 2007. Shotgun DNA sequencing bearing fruits: probing the dynamics of genome size. Frankfurt University, Frankfurt, Germany.
- Goettel, W. and Messing, J. 2008. Structural and transcriptional analysis of the complex P1-wr cluster in maize, Plant and Animal Genome XVI, San Diego, California.
- Miclaus, M., Xu, J., Messing, J. 2008. Short and long-distance placement of gene copies in the maize genome, 50th Annual Maize Genetics Conference, Washington, D.C.
- Miclaus, M., Xu, J., Messing, J., 2009. Shift of Gene Expression in The Evolution Of A Multigene Family of Maize, Plant and Animal Genome XVII, San Diego, California.
- Wu, Yongrui, Messing, J. 2009. Redundant Function of Gamma and Beta Zeins in Stabilization of Protein Body Formation, 51st Annual Maize Genetics Conference, St. Charles, IL.
- Xu, J.-H., Messing, J., 2009. Evolution of Cereal Storage Proteins, 51st Annual Maize Genetics Conference, St. Charles, IL.
- Xu, J-H, Messing, J., 2009. Expansion and Divergence of the Prolamin Gene Family in Different Subfamilies of the Grasses, Plant and Animal Genome XVIII, San Diego, California.

Conferences/Invited Lectures

- MRC Laboratory of Mol Biol., Special Lecture, Cambridge, England, October 1981.
- University of Heidelberg, Society of Mol. Biol., Special Lecture, Heidelberg, W. Germany, October 1981.
- Roche Institute of Mol. Biol., Nutley, NJ, October 1981.
- Iowa State University, MCDB, Ames, IA, November 1981.
- 3M Company, St. Paul, MN, November 1981.
- Danish Academy of Technical Sciences, Copenhagen, Denmark, December 1981.
- The Polytechnical University, Microbiology, Lyngby, Denmark, December 1981.
- Carlsberg Laboratories, Copenhagen, Denmark, December 1981.
- Medical Nobel Institute, Karolinska Institutet, Stockholm, Sweden, December 1981.
- University of Freiburg, Biology III, Freiburg, W. Germany, December 1981.
- University of Munich, Biochemistry, Munich, W. Germany, December 1981.
- New England Nuclear, Newton, MA, January 1982.
- Harvard University, Biolabs, Cambridge, MA, January 1982.
- Canadian Biochemical Society, Mount St. Anne, Quebec, February 1982.
- Applied Molecular Genetics, Newbury Park, CA, April 1982.
- Conference on Site Directed Mutagenesis, Cold Spring Harbor, NY, May 1982.
- Brookhaven National Laboratory, Upton, NY, May 1982.
- Pillsbury Company, Minneapolis, MN, June 1982.
- Conference on Genetic Engineering of Plants, Davis, CA, August 1982.
- Monsanto Company, St. Louis, MI, October 1982.
- Maize Genetics Meeting, Allerton, IL, March 1983.
- Columbia University, Human Genetics, New York, NY, March 1983.
- Allied Company, Syracuse, NY, March 1983.
- Molecular Genetics, Inc., Minnetonka, MN, May 1983.
- Advanced Cloning Course, Cold Spring Harbor, NY, August 1983.

University of Tennessee, Microbiology, Knoxville, TN, October 1983.
University of Kansas, Biochemistry, Kansas City, KA, November 1983.
University of Missouri, Biochemistry, Columbia, MI, November 1983.
University of Florida, Vegetable Crops, Gainesville, FL, December 1983.
University of Minnesota, Biochemistry, Duluth, MN, January 1984.
Rutgers University, Waksman Institute, Piscataway, NJ, January 1984.
Carnegie Institution of Washington, Embryology, Baltimore, MD, January 1984
Maize Genetics Meeting, Urbana, IL, March 1984.
Plant Molecular Biology Symposium, Boulder, CO, April 1984.
University of California Riverside, Biological Sciences, Riverside, CA, April 1984.
Johns Hopkins University, Biology, Baltimore, MD, April 1984.
Workshop on Plant Mitochondrial DNA, Melrose, Scotland, May 1984.
University of Edinburgh, Molecular Biology, Edinburgh, Scotland, May 1984.
University of Gent, Genetics, Gent, Belgium, May 1984.
Max Plank Institute for Plant Breeding, Cologne, W. Germany, May 1984.
University of Munich, Biochemistry, Munich, W. Germany, June 1984.
Plant Molecular Biology Course, Cold Spring Harbor, NY, June 1984.
Canadian Biochemical Society, Saskatoon, Canada, June 1984.
Hoechst Company, Biotechnology, Frankfurt, W. Germany, July 1984.
Hutchinson Cancer Research Center, Seattle, WA, August 1984.
6th International Conference of Virology, Symposium Speaker, Sendai, Japan, September 1984.
University of Kyoto, Nucl. Acid Res., Kyoto, Japan, September 1984.
American Society of Cereal Chemists, Symposium Speaker, Minneapolis, MN, October 1984.
Pioneer Hi-Bred International, Biotechnology, Des Moines, IA, October 1984.
Mid-Atlantic Plant Molecular Biology Society, Symposium Speaker, October 1984.
University of Kentucky, Biological Sciences Lecture Series, Lexington, KY, December 1984.
Northern Illinois University, Biological Sciences, DeKalb, IL, December 1984.
Texas Medical Center, Burt Lecture, Houston, TX, January 1985.
National Research Council, Ottawa, Canada, March 1985.
Cancer Research Institute, Sapporo Medical College, Sapporo, Japan, April 1985.
Tokyo University, Tokyo, Japan, April 1985.
Kanazawa University, Kanazawa, Japan, April 1985.
Osaka University, Osaka, Japan, April 1985.
Kyushu University, Fukuoka, Japan, April 1985.
University of Montreal, Montreal, Canada, May 1985.
Queens University, Beckman Lecture, Kingston, Canada, May 1985.
New Jersey Society of Biotechnology, University of Medicine and Dentistry of New Jersey, Piscataway, NJ, May 1985.
Plant Molecular Biology Course, Cold Spring Harbor, NY, June 1985.
Advanced Cloning Course, Cold Spring Harbor, NY, June 1985.
DNA Plant Technology Corporation Scientific Advisory Board Conference, New York, NY, September 1985.
Fourth Carolina Conference on Gene Transfer and Expression, University of North Carolina at Chapel Hill, NC, October 1985.
First International Congress of Plant Molecular Biology, Savannah, GA, October 1985.
Working Conference on Cancer Research in New Jersey, New Jersey State Commission on Cancer Research, Somerset, NJ, November 1985.
University of Nijmegen, The Netherlands, December 1985.
International Congress on Computers in Biotechnology, Baltimore, MD, January 1986.
University of Toronto, Department of Microbiology, Faculty of Medicine, Toronto, Canada, March 1986.

New England BioLabs, Beverly, MA, April 1986.
Department of Microbiology, University of Medicine and Dentistry of New Jersey, Newark, NJ, May 1986.
Fisher Scientific, Biotechnology Division, New Brunswick, NJ, May 1986.
1986 Carolina Workshops, University of North Carolina, Chapel Hill, NC, May 1986.
Biotechnology: Perspectives, Policies and Issues Symposium, University of Florida, Gainesville, FL, June 1986.
First International Symposium on Chromatin Structure of Plant Genes, Frankfurt, West Germany, August 1986.
EMBO Workshop on Plant Storage Protein Genes, Freiburg, West Germany, September 1986.
DNA Plant Technology Corp. Annual Scientific Advisory Board Workshop, Philadelphia, PA, September 1986.
Princeton University, Graduate Program in Molecular Biology, Annual Retreat, Tannersville, PA, October 1986.
Mid-America Molecular Biology Colloquium, Afton, OK, October 1986.
Cornell University, Plant Biology Section, Ithaca, NY, November 1986.
University of Maine, Departments of Biochemistry and Botany, Orono, ME, December 1986.
Plant Molecular Biology Conference, Auckland, New Zealand, February 1987.
Molecular Genetics, Inc., Minnetonka, MN, March 1987.
Institute for Chemical Research, Kyoto University, Kyoto, Japan, April 1987.
XIV International Botanical Congress, West Berlin, July 1987.
DNA Plant Technology Corp., Annual Scientific Advisory Board Conference, Philadelphia, PA, September 1987.
Lake Tahoe Symposium: Advances in Recombinant DNA Technology, Lake Tahoe, NV, September 1987.
Cook Seminar Series on Biotechnology, New Brunswick, New Jersey, October 1987.
Maize Genetics Conference, Delavan, WI, March 1988.
Third Chemical Congress of North America, Toronto, Canada, June 1988.
14th International Congress of Biochemistry, Prague, Czechoslovakia, July 1988.
National Cancer Institute, Frederick Cancer Research Facility, Frederick, MD, November 1988.
Integrated Genetics, Framingham, MA, January 1989.
Maize Genetics Meeting, Delavan, WI, March 1989.
Ciba-Geigy Corporation, Summit, NJ, April 1989.
City College of New York, NY, May 1989.
Workshop on Trends in Comparative Molecular Genetics, Liblice, Czechoslovakia, June 1989.
Institute für Genbiologische Forschung, Berlin, West Germany, June 1989.
Carlsberg Laboratory, Copenhagen, Denmark, June 1989.
Colloquium Series of the Governor's School in the Sciences at Drew University, Madison, NJ, August 1989.
Marquette University, Milwaukee, WI, September 1989.
EniChem Americas, Inc., Monmouth Junction, NJ, October 1989.
Wolf Trap Genome Sequencing Conference, Vienna, VA, October 1989.
University of Arizona, Department of Plant Sciences, Tucson, AZ, February 1990.
University of California, Department of Botany, Davis, CA, February 1990.
University of California, Department of Plant Biology, Berkeley, CA, February 1990.
University of Medicine and Dentistry of New Jersey-Robert Wood Johnson Medical School, Piscataway, NJ, March 1990.
Maize Genetics Meeting, Delavan, WI, March 1990.
Walter Reed Hospital, Washington, DC, April 1990.

Continuing Education Workshop, Waksman Institute, Rutgers University, Piscataway, NJ, May 1990.
Princeton University, Molecular Biology Department, Princeton, NJ, May 1990.
Pioneer Hi-Bred International, Inc., Johnston, IA, July 1990.
Drosophila Genome Conference, Madison, WI, August 1990
20th Meeting of the Federation of European Biochemical Societies, Budapest, Hungary, August 1990.
Institute of Biochemistry, Biological Research Center, Szeged, Hungary, September 1990.
Agricultural Biotechnology Institute, Gödöllő, Hungary, September 1990.
DNA Plant Technology Corp., Cinnaminson, NJ, October 1990.
State University of New York, Department of Biological Sciences, Buffalo, NY, October 1990.
University of Heidelberg, Germany, November 1990.
University of Gent, Belgium, December 1990.
Free University of Berlin, Germany, December 1990.
Institute of Genetics and Plant Breeding, Gatesleben, Germany, December 1990.
University of Florida, Interdisciplinary Center for Biotechnology Research, Gainesville, January 1991.
University of Minnesota, Plant Molecular Genetics Institute, St. Paul, MN, March 1991.
Pharmacia P-L Biochemicals Inc., Milwaukee, WI, March 1991.
33rd Annual Maize Genetics Meeting, Delavan, WI, March 1991.
Thomas Jefferson University, Jefferson Cancer Institute, Philadelphia, PA, December 1991.
New York Area Plant Molecular Biology Meeting, New York, NY January 1992.
University of Pennsylvania, Department of Biology, Philadelphia, PA, March 1992.
34th Annual Maize Genetics Meeting, Pacific Grove, CA, March 1992.
Temple University, Department of Biology, Philadelphia, PA, April 1992.
New Jersey Consortium of County College Biology Educators, County College of Morris, Randolph, NJ, May 1992.
Institut für Genbiologische Forschung, Berlin, Germany, August 1992.
Max-Planck-Institut für Züchtungsforschung, Köln, Germany, September 1992.
Institut für Genetik, Universität zu Köln, Köln, Germany, September 1992.
Friedrich Miescher-Institut in Basel, Switzerland, September 1992.
Institut für Biologie III, Albert-Ludwigs-Universität, Freiburg, Germany, September 1992.
Cold Spring Harbor Laboratory, Cold Spring Harbor, NY, November 1992.
New York Area Plant Molecular Biology Meeting, New York, NY January 1993.
Heterosis Conference, Pioneer Hi-Bred International, Inc., Johnston, IA, February 1993.
35th Annual Maize Genetics Meeting, St. Charles, IL, March 1993.
RWJ Medical School, Department of Biochemistry, Piscataway, NJ, May 1993.
NATO Advanced Science Institute on Plant Molecular Biology, Mallorca, Spain, May 1993.
Institute des Sciences Vegetales, Centre National de la Recherche Scientifique, Gif Sur Yvette, France, May 1993.
Pharmacia Biotech AB, Uppsala, Sweden, June 1993.
Royal Institute of Technology, Biochemistry, Stockholm, Sweden, June 1993.
Gordon Research Conference on Plant Cell and Tissue Culture, Plant Transgenes, Wolfeboro, NH, June 1993.
CSIRO Division of Plant Industry in Canberra, Australia, July 1993.
American Society for Biochemistry and Molecular Biology (ASBMB) Fall Symposium, Keystone, CO, October 1993.
New York Area Plant Molecular Biology Meeting, New York, NY, January 1994.
Center for Human Genome Studies, Los Alamos National Laboratory, Los Alamos, NM, January 1994.

Max-Planck-Institut, Munich, Germany, March 1994.
36th Annual Maize Genetics Meeting, St. Charles, IL, March 1994.
Texas A&M University, Houston, TX, December 1994.
New York Area Plant Molecular Biology Meeting, New York, NY, January 1995.
DIMACS Distinguished Lecture Series, Rutgers University, Piscataway, NJ, January 1995.
Japan-USA Workshop on Modification of Gene Expression and Non-Mendelian Inheritance, Tsukuba, Ibaraki, Japan, January 1995.
Institute of Chemical Research, Kyoto University, Kyoto, Japan, January 1995.
Kazusa DNA Research Institute, Chiba, Japan, January 1995.
37th Annual Maize Genetics Meeting, Pacific Grove, CA, March 1995.
University of California, Department of Plant Sciences, Berkeley, CA, May 1995.
Gordon Research Conference on Plant Cell Genetics and Development, Wolfeboro, NH, June 1995.
University of Copenhagen, Institute of Molecular Biology, Denmark, November 1995.
Free University of Amsterdam, The Netherlands, November 1995.
University of Nijmegen, The Netherlands, November 1995.
38th Annual Maize Genetics Meeting, St. Charles, IL, March 1996.
Pharmacia Biotech, Uppsala, Sweden, April 1996.
Westfälische Wilhelms-Universität Münster, Germany, May 1996.
Albert-Ludwigs-Universität Freiburg, Germany, May 1996.
New York Area Plant Molecular Biology Meeting, New Brunswick, NJ, June 1996.
Gordon Research Conference on Plant Cell Genetics and Development, Wolfeboro, NH, June 1996.
National Corn Genome Initiative, Des Moines, IA, August 1996.
Max-Planck-Institut für Züchtungsforschung, Köln, Germany, September 1996.
Johann Wolfgang Goethe-Universität, Frankfurt, Germany, September 1996.
19th Annual Symposium in Plant Physiology at University of California, Riverside, January 1997.
New York Area Plant Molecular Biology Meeting, New York, NY, January 1997
39th Annual Maize Genetics Meeting, Clearwater Beach, FL, March 1997.
Peking University, Beijing, China, March 1997.
National Laboratory of Plant Molecular Genetics, Shanghai, China, March 1997.
National Academy of Sciences Colloquium, Beckman Center, Irvine, CA, June 1997.
Gordon Research Conference on Plant Cell Genetics and Development, Henniker, NH, June 1997.
Sussex Symposium and Reunion, University of California, Berkeley, CA, June 1997.
Gordon Research Conference on Epigenetics, Plymouth, NH, August 1997.
5th International Congress of Plant Molecular Biology, Singapore, September 1997.
University of Missouri-Columbia, MO, November 1997.
Institut für Pflanzengenetik und Kulturpflanzenforschung, Gatersleben, Germany, December 1997.
Genomforschung bei Getreide, Alterode/Harz, Germany, December 1997.
Kazusa DNA Research Institute, Japan, February 1998.
Center for Research Institutes, Tsukuba, Japan, February 1998.
40th Annual Maize Genetics Meeting, Lake Geneva, WI, March 1998.
Friedrich Miescher Institute, Basel, Switzerland, June 1998.
USDA/Cooperative State Research, Education and Extension Service public forum, Washington, DC, July 1998.
Mid-Atlantic Plant Molecular Biology Society Symposium, Laurel, MD, July 1998.
International Symposium on Rice Germplasm Evaluation and Enhancement, Stuttgart, AR, September 1998.
10th International Genome Sequencing and Analysis Conference, Miami, FL, September 1998.

Department of Molecular Biotechnology, University of Washington, Seattle, WA,
November 1998.

Computational Biology Seminar Series, University of Washington, Seattle, WA,
November 1998.

International Plant and Animal Genome VII Conference, San Diego, CA, January 1999.

International Rice Genome Workshop, Tsukuba, Japan, February 1999.

University of Florida, Gainesville, February 1999.

Cold Spring Harbor Laboratory, Cold Spring Harbor, NY, March 1999.

Maize Genetics Retreat at Allerton, Monticello, IL, March 1999.

41st Annual Maize Genetics Meeting, Lake Geneva, WI, March 1999.

Texas A&M University, College Station, TX, April 1999.

Boyce Thompson Institute at Cornell University, Ithaca, NY, April 1999.

Plant Biological and Molecular Processes National Program Workshop, St. Louis, MO,
June 1999.

XVI International Botanical Congress, St Louis, MO, August 1999.

International Program on Rice Biotechnology, Phuket, Thailand, September 1999.

German Congress of Sports Medicine and Prevention, Freiburg, Germany, September
1999.

Cornell University, Ithaca, NY, November 1999.

Biotechnology in the Year 2000 and Beyond meeting, Washington, DC, November 1999.

Max-Planck-Institut für Molekulare Pflanzenphysiologie, Golm, Germany, January 2000.

International Plant and Animal Genome VIII Conference, San Diego, CA, January 2000.

National Institute of Agricultural Science and Technology, Suwon, Korea, February
2000.

University of Wisconsin, Madison, WI, February 2000.

42nd Annual Maize Genetics Meeting, Coeur d'Alene. ID, March 2000.

Festveranstaltung und zum Symposium at the Institut für Pflanzengenetik und
Kulturpflanzenforschung, , Gatersleben, Germany, September 2000.

International Plant and Animal Genome IX Conference, San Diego, CA, January 2001.

43rd Annual Maize Genetics Meeting, Lake Geneva, WI, March 2001.

Kiwanis Club, Milltown-North Brunswick, August 2001.

44th Annual Maize Genetics Meeting, Orlando, FL, March 2002.

MIT, Boston, Massachusetts, October 2002.

University of Arizona, Tucson, Arizona, November 2002.

Plant & Animal Genome XI, San Diego, CA, January 2003.

Advances in Genome Biology and Technology, Marco Island, FL, February 2003.

Ege University, Izmir, Turkey, February 2003.

45th Annual Maize Genetics Conference, Wisconsin, Lake Geneva March, 2003.

Pioneer Hybrid/Dupont, Des Moines, Iowa, March 2003.

Monsanto, Mystic, CT, May 2003.

Technical University of Munich, Munich, Germany, June 2003.

University of Florida, Gainesville, Fl, November 2003.

University of Minnesota, December 2003.

Plant & Animal Genome XII, San Diego, CA, January 2004.

Advances in Genome Biology & Technology, Marco Island, FL, February 2004.

46th Annual Maize Genetics Conference, Mexico City, Mexico, March, 2004.

Oxford University, Oxford, United Kingdom, May, 2004.

9th International Symposium on Plant Seeds, Gatersleben, Germany, May, 2004.

DAS Dow Agricultural Sciences, Indianapolis, Indiana, November , 2004.

9th Evolutionary Biology Meeting, Marseilles, France, September, 2005.

48th Annual Maize Genetics Conference, Asilomar Conference Grounds, Pacific Grove,
CA, March 2006.

Symposium Heterosis in Plants, Potsdam, Germany, May 2006.

University of Hamburg, Hamburg Germany, May 2006.

Virginia Tech, Blacksburg, Virginia, August 2006.
Hong Guang Research Center, School of Life Sciences, Shanghai University, Shanghai, China, November 2006.
Gene Research Center, Chinese Academy of Sciences, Shanghai, China, November 2006.
Shanghai Institute of Plant Physiology, Chinese Academy of Sciences, Shanghai, China, November 2006.
Brookhaven National Laboratory, Brookhaven, NY, May 2007.
BASF, Research Triangle Park, NC, May 2007.
The University of Tübingen, Germany, August 2007.
Frankfurt University, Frankfurt, Germany, August 2007.
50th Annual Maize Genetics Conference, Washington DC, February 2008.
Princeton University, Princeton New Jersey, March 2008.
4th EPSO conference “Plants for Life,” Hyeres, France, June 2008
IVth National Bioengineering Congress, Izmir, Turkey, October 2008.
Universite De Geneve, Geneva, Switzerland, October 2008.
Universite de Lusanne, Switzerland, October 2008
University of Freiburg, 2008. Freiburg, Germany, October 2008.
China Agricultural University, Beijing, China, November 2008.
Chinese Academy Agricultural Sciences, Beijing, China, November 2008.
Plant & Animal Genome XVII, San Diego, CA, January 2009.
Microbiology Symposium, New Brunswick, NJ, January 2009.
51st Annual Maize Genetics Conference, St. Charles, Illinois, March 2009.
1st National Conference on Biotechnology, Lima, Peru, May 2009
XXIth International Conference EUCARPIA, Bergamo, Italy, June 2009.
International Plant Molecular Biology Meeting, St. Louis, MI, October 2009.