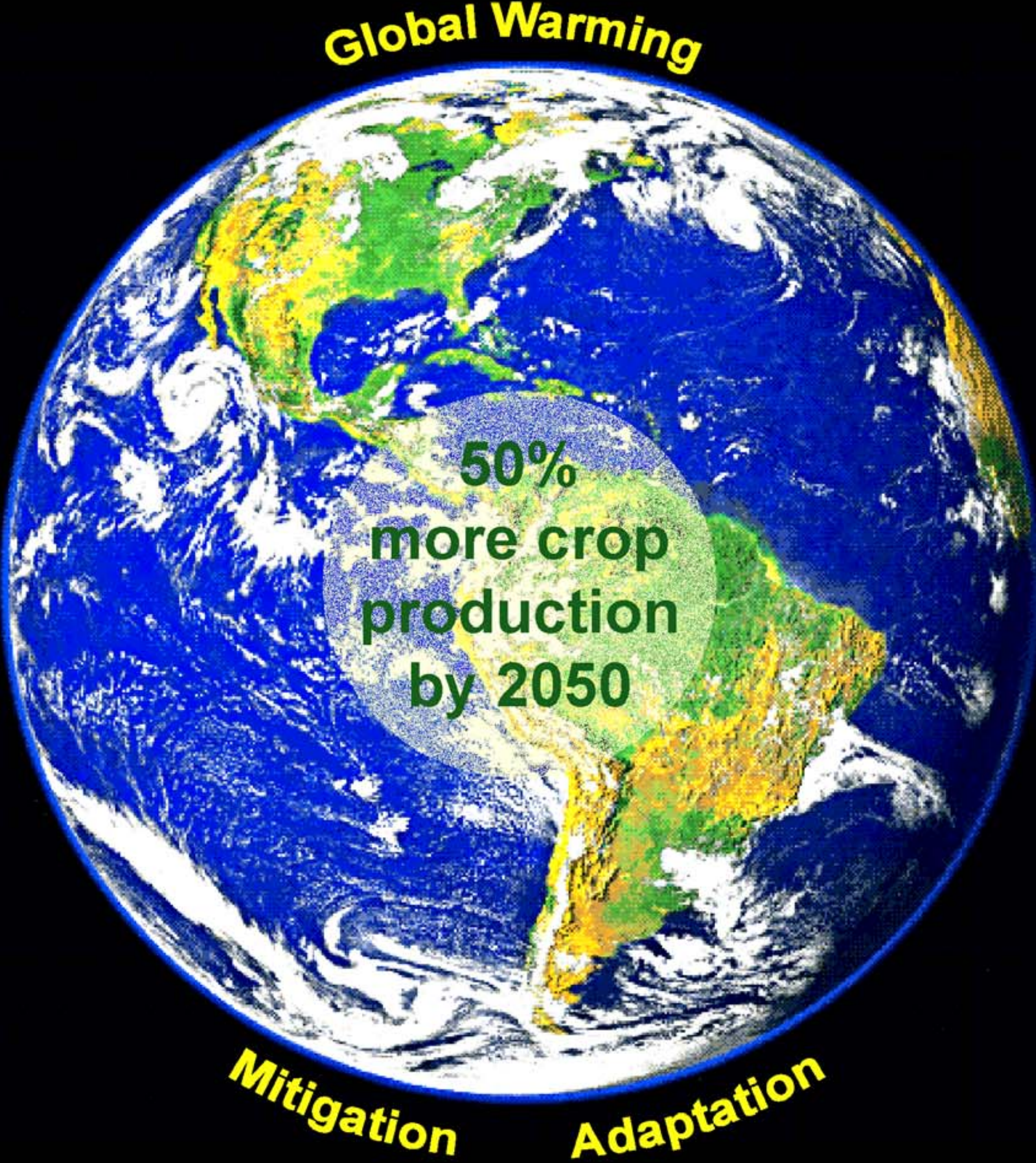
NABC Report 21

Adapting Agriculture to Climate Change



Research Modeling Policy Ethics Education

Edited by Allan Eaglesham & Ralph W.F Hardy

2009

National Agricultural Biotechnology Council Report

Cover: World agriculture faces the dual challenges of increasing crop production and addressing climate change. Increasing population, diets inclusive of more animal-based foods, and increased manufacture of biobased industrial products will require an increase in crop production of at least 50% by 2050. Agriculture produces approximately 10% of greenhouse gasses (GHGs) (CO_2, CH_4, N_2O). Our plant and animal agricultural systems will need to both mitigate production of GHGs and adapt to the stresses of climate change as well as take advantage of the benefits. Research, modeling, policy, ethics and education—as discussed in this volume—will be key to meeting these challenges.

NABC Report 21

Adapting Agriculture to Climate Change

Proceedings of the twenty-first annual conference of the National Agricultural Biotechnology Council, hosted by the College of Agriculture and Bioresources, University of Saskatchewan, Saskatoon, Saskatchewan, June 24–26, 2009

Edited by
Allan Eaglesham & Ralph W.F. Hardy

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NABC Report 21

Adapting Agriculture to Climate Change

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National Agricultural Biotechnology Council

Providing an open forum for exploring issues in agricultural biotechnology

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ACKNOWLEDGMENTS

NABC's twenty-first annual meeting—*Adapting Agriculture to Climate Change*—was hosted by Graham Scoles at the University of Saskatchewan, Saskatoon, Saskatchewan, with superb administrative assistance from Mary Anne Ledsham. We are most grateful to them for a highly successful conference.

Thanks are due to the members of the planning committee[1] for an excellent program and first-rate choice of speakers: Graham Scoles (program chair), Malcolm Devine (Performance Plants, Inc.), Ron Kehrig (Enterprise Saskatchewan), Wilf Keller (Genome Prairie), Jerome Konecsni (National Research Council of Canada), Susanne Lipari (NABC), Ian McPhadden (Ag-West Bio, Inc.), Dan Pennock (University of Saskatchewan), Sonny Ramaswamy (Purdue University), Carol Reynolds (Genome Prairie), Andrew Van Kessel (University of Saskatchewan) and Elaine Wheaton (Saskatchewan Research Council).

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Impeccable smoothness of the proceedings resulted from excellent behind-the-scenes efforts of the following members of staff of the University of Saskatchewan:

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Ralph W.F. Hardy
President
NABC

Allan Eaglesham
Executive Director
NABC

December 2009

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[1] RWFH and AE served on the planning committee.

[2] AE served as a workshop recorder.

PREFACE

As illustrated on the cover, world agriculture faces the dual challenges of increasing crop production and addressing climate change. Increasing population, diets inclusive of more animal-based foods, and increased manufacture of biobased industrial products will require increased crop production of at least 50% by 2050. Agriculture produces approximately 10% of greenhouse gasses (GHGs) (CO_2, CH_4, N_2O). Our plant and animal agricultural production systems will need to mitigate production of GHGs and adapt to the stresses of climate change, as well as take advantages of benefits. A bigger question for agriculture than change itself will be how to deal with the unpredictability of alterations in temperature, precipitation levels and patterns, and growing season and of extreme weather events. Furthermore, the challenges posed by climate change must be met by agriculture as the industry deals with declining reserves of fossil fuels and fertilizers.

NABC's twenty-first annual meeting brought representatives of academia, industry and government agencies to the campus of the University of Saskatchewan in Saskatoon, Canada, June 24–26, 2009, to address issues that will be key to meeting these challenges: research, modeling, policy, ethics and education. *Adapting Agriculture to Climate Change*—NABC's first conference to focus on climate change—stimulated vigorous discussions in the formal plenary sessions and the less-formal "breakout" workshops. The conference was structured in four modules designed to frame the questions and develop insights regarding the issues. Speakers representing expertise in diverse aspects of each topic presented their viewpoints:

Module 1 *Climate Change Overview and Projections*

2 *Genetic Approaches to Crop Adaptation*

3 *Other Approaches to Adaptation*

4 *Ethics, Policy, Carbon Credits*

Following the plenary presentations in modules 2–4, invited panelists reflected on the speakers' comments, and all of the modules concluded with comments and questions from the audience. As is traditional for NABC meetings, participants gathered in smaller "breakout" workshops for further discussions of issues raised in the plenary and Q&A sessions.

The *Student Voice at NABC* program provides grants of up to $750 to graduate students at NABC-member institutions (one student per institution) to offset travel and lodging expenses. Also, registration fees are waived for grant winners. The *Student Voice* delegates attended the plenary sessions and breakout workshops at NABC 21, and then met as a group to identify current and emerging issues relevant to the conference subject matter[1].

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[1] Information on the *Student Voice at NABC 22* will be available at http://nabc.cals.cornell.edu/studentvoice/.

This volume contains an overview of the conference, a summary of the breakout-workshop discussions, manuscripts provided by the speakers, including the banquet presentation, and the *Student Voice* report. Transcripts of the panel discussions and Q&A sessions are included.

NABC 22—*Promoting Health by Linking Agriculture, Food and Nutrition*—will be hosted by the University of California at Davis, June 14–16, 2010[2].

Allan Eaglesham	Ralph W.F. Hardy
Executive Director	*President*
NABC	*NABC*

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[2] Further information may be accessed at http://nabc.ucdavis.edu/.

CONTENTS

PART I–CONFERENCE OVERVIEW

Overview of NABC 21: Adapting Agriculture to Climate Change

Allan Eaglesham & Ralph W.F. Hardy
National Agricultural Biotechnology Council
Ithaca, New York

NABC's twenty-first annual conference convened in Saskatoon, June 24–26, 2009, hosted by the College of Agriculture and Bioresources at the University of Saskatchewan. The focus was mainly on the complex issues involved in adapting crop agriculture to climate change, with minor comments on mitigation; animal agriculture was not addressed. The sixty delegates were welcomed by Graham Scoles (NABC-21 program chair, dean of the College of Agriculture and Bioresources), Peter MacKinnon (president of the University), Alanna Koch (deputy minister of agriculture for Saskatchewan) and Allan Eaglesham (NABC executive director, for NABC President Ralph Hardy). Plenary sessions were held on the afternoon of June 24, the morning and afternoon of June 25, and the morning of June 26.

The keynote speaker at the June 25 banquet—held at the Western Development Museum—was Sylvain Charlebois (associate dean and director of the Levene Graduate School of Business at the University of Regina, Regina). whose presentation was titled *Opportunities of the Commons: Agriculture's New Frontier*.

The conference was structured in four modules, after each of which two parallel breakout sessions were scheduled (see p. 13). The breakout session after Module 2 was cancelled due to over-run of the prior, lively Q&A session. Three panelists reacted to the plenary presentations with brief remarks after Modules 2, 3 and 4, after which Q&A sessions involved audience participation (including Module 1).[1]

Module 1—*Climate Change Overview and Projections*—comprised presentations by Francis Zwiers (Canadian Centre for Climate Modelling and Analysis, Toronto, *Our Evolving Climate*), Raymond Desjardins (Agriculture and Agri-Food Canada, Ottawa, *The Impact of Agriculture on Climate Change*), and Linda Mearns (Institute for the Study of Society and Environment, Boulder, *The Impact of Climate Change on Agriculture*).

In Module 2—*Genetic Approaches to Crop Adaptation*—presentations were made by Tim Sutton (University of Adelaide, Adelaide, *Functional Genomics and Abiotic Stress Tolerance in Cereals*), Malcolm Devine (Performance Plants, Saskatoon, *Enhancing Crop*

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[1] Transcripts of the panelists' remarks and the Q&A sessions will be included in the proceedings volume, *NABC Report 21*.

Productivity Through Increased Abiotic Stress Tolerance and Biomass), and Michael Metzlaff (Bayer BioScience NV, Ghent, *Adapting Crops to Climate Change*).

The speakers in Module 3—*Other Approaches to Adaptation*—were Don Smith (McGill University, Montreal, *Living With It: Adapting Crop-Production Systems to Emerging Climate Change*), Jeffrey White (US Arid Land Agricultural Research Center, Maricopa, *Adapting Cropping Patterns to Climate Change*), and Rattan Lal (Ohio State University, Columbus, *Soil and Water Management Options for Adaptation to Climate Change*)

Presentations in Module 4—*Ethics, Policy, Carbon Credits*—were made by Harold Coward (University of Victoria, Victoria, *Ethical Issues in Adaptation and Mitigation Responses to Climate Change*), Gordon McBean (University of Western Ontario, London, *Adapting to Climate Change: The Challenges and Opportunities in an Uncertain Policy Environment*) and Benjamin Gramig (Purdue University, West Lafayette, *Greenhouse Gas Emissions Offsets from Agriculture: Opportunities and Challenges*)

Issues of interest raised by the speakers included the following.

Climate-Change Overview and Projections

- That global warming is occurring is unequivocal. The evidence comes from air temperatures and ocean temperatures, from reductions in the amounts of ice and snow on the surface of the planet, and from changes in sea level because additional water is being stored in the oceans and because the oceans are being warmed. Although there is a great deal of natural internal variability in the system, strong evidence suggests that human activity has been driving these temperatures upwards for the past century.
- Over the past 100 years, the concentration of carbon dioxide (CO_2) in the atmosphere has risen by approximately 100 ppm. That CO_2 has come from our use of fossil fuels and of the land surface, causing movements of carbon from fossil and soil reservoirs into the atmosphere.
- Using computer-simulation models, we can do a pretty good job of reproducing the history of the twentieth century on a global scale by taking into account the effects of human and natural external factors on the climate system. If we leave out human factors and consider only the natural factors—solar and volcanic forcing—then we cannot explain the rapid warming that occurred during the latter part of the twentieth century.
- Aerosols that are abundant in the environment as dust particles (from bare soil and plant residues), or as anthropogenic residues of combustion (from crop burning), can have a significant cooling effect. They have a direct effect on the radiation budget by scattering and absorbing short-wave and long-wave radiation. They also have an indirect radiative effect by influencing cloud formation, which may then lead to changes in the incoming solar radiation.
- Globally, agriculture accounts for 13% of the radiative forcing related to greenhouse gases (GHGs); in Canada and the United States it accounts for 6% to 8%.

The GHG emissions in Canada and the United States are mainly in the form of methane (CH_4) and nitrous oxide (N_2O). Agricultural sources such as animal husbandry, manure management and agricultural soils account for about 52% of global CH_4 and 84% of global N_2O emissions. In the past, deforestation and intensive agriculture (*e.g.* grassland cultivation) have contributed significantly to the increase in atmospheric carbon dioxide CO_2. For example, until the 1970s, more CO_2 had been released into the atmosphere from agricultural activities than from fossil-fuel burning.

- Agricultural activities can influence climate through land-use change, which can modify the albedo of the Earth's surface. The albedo in an agricultural context depends on a variety of factors including crop type, crop, management practice, surface condition, time of day and time of year.
- In the past 20 years, about 75% of the CO_2 emissions have been attributed to fossil-fuel burning and the remainder to land-use changes. The major impacts of agricultural land-use change are occurring in tropical rainforest regions such as Brazil, Congo, and Indonesia where native rainforests are being cleared for cultivation and pasture. Tropical deforestation, which now exceeds 13 Mha per year, is a substantial source of CO_2. It also causes a moderate increase in albedo, which causes cooling of the air; however, this cooling is more than offset by warming of the air through reduction in evapotranspiration and through CO_2 emissions associated with deforestation.
- Fifteen years ago, the focus was on what to expect in the year 2100. Now there's more emphasis on the next 25 years, which is an indication of how much more seriously the problem is being taken. It is no longer an academic exercise.
- A 2007 report on how climate change will affect agriculture in the Canadian prairies stated, "The net impacts are not clear and depend heavily on assumptions including the effectiveness of adaptation." Per the title of this conference: adaptation may have tremendous effects in terms of crop yields, agricultural economics and food security.
- Extreme events in agriculture have received particular emphasis in the past 10 years. For example, the drought in the Canadian prairies in 2001–2002 caused losses in agricultural production equivalent to $3.6 billion. Net farm income was negative for several provinces. However, adaptation measures could not completely offset the drought impact. This demonstrates that, even in advanced western society, increased adaptive capacity will be important.

Genetic Approaches to Crop Adaptation

- Since 2001/02, much of Australia's most productive agricultural land, primarily in the southeast, has experienced conditions of higher-than-average temperatures and lower-than-average rainfall; after several preceding years of drought, 2007 was one of the hottest growing seasons on record across much of Southern Australia, with crop losses much larger than expected. This trend of declining rainfall and increasing temperatures is predicted to continue, emphasizing a need for scientific approaches to develop germplasm adapted to hostile conditions.

- Historically, improvement of tolerance to abiotic stresses has been a major target of plant-breeding programs globally. The major challenge, however, results from the complex nature of abiotic-stress-tolerance traits and the difficulty in dissecting them into manageable genetic components amenable to molecular breeding.
- Dissecting drought tolerance to the level of a single gene or group of genes amenable to genetic engineering will be difficult. A major challenge in the use of functional genomics to enhance the development of drought tolerance is to define the system and focus on key traits of interest.
- Various analyses suggest that increasing temperatures will pose a major constraint to crop production in the future. The warmest summers observed in the tropics and subtropics in the past century may be seen as normal by the end of the twenty-first century.
- Despite the trends of higher temperatures in many regions, protection against the devastating effects of low temperatures, particularly during the sensitive phases of seedling growth and crop maturation, remains an important focus area for crop improvement.
- Water-use efficiency is being recognized as a critically important trait in areas where crop production relies on dwindling supplies of sub-surface irrigation water or where there is competition for water between urban and agricultural demands.
- Some stress-protection mechanisms in plants appear to confer tolerance of multiple stresses, for example through effects on energy balance or detoxification of reactive oxygen species generated upon exposure to stress. Down-regulation of poly(ADP-ribose) polymerase (PARP) in *Arabidopsis* and canola increased tolerance of heat, drought and high light.
- In C_3 crops, photosynthesis is less than optimally efficient because of photorespiration, whereby a third of the fixed carbon is lost. The possibility of decreasing photorespiration is under research, thereby saving energy and improving the plant's resistance to stresses.
- Canola plants of a particular variety were grown under stress and non-stress conditions and separated into good performers (low respiration rate) and bad performers (high respiration rate) over several generations, producing a population with higher energy homeostasis under stress conditions. Analysis revealed that epigenetic variants had been selected, not mutants, with DNA methylation changes that correlate with good and bad performance. These changes occurred in coding regions of genes involved in stress response. When the superior epigenetic variants were crossed with hybrid lines, heterosis resulted in more leaf material and better growth under a range of stress conditions.

OTHER APPROACHES TO ADAPTATION

- Increased productivity of crop plants due to increased concentration of atmospheric CO_2 may force corresponding increases in fertilizer demand (especially for non-legumes), in order to achieve higher yield potentials. On the other hand, higher nitrogen-use efficiency under elevated CO_2 levels may mitigate increased demands for fertilizers. Application of plant-growth-promoting rhizobacteria (biofertilizers) and understanding signaling between bacteria and plants may also lead to improved crop productivity and, as a result, increase sequestration of carbon in roots; some of these signals also have the potential to increase legume nitrogen fixation, reducing nitrogen-fertilizer applications in the long term and, therefore, reducing N_2O emissions.
- Rising atmospheric temperatures will have both direct and indirect consequences for crop plants. Greater heat stress will likely be experienced more often by temperate-adapted species, potentially reducing their photosynthetic efficiency and increasing their susceptibility to pests, disease, and competition from weedy species. This will probably result in a need for more-frequent pesticide applications, more-careful pest monitoring, and development—including by genetic engineering—of pest- and disease-resistant crops.
- The northerly migration of pest and weed species in response to warmer conditions at higher latitudes poses serious challenges to growers unfamiliar with their management. Insect pests may increase their numbers of generations produced *per annum*, thereby increasing insect densities and associated predation of crops. Temperature rise and elevated CO_2 concentration could increase plant damage from pests in future decades. Weeds show a larger range of responses to elevated CO_2 than do crops, due to their greater genetic diversity. Increased wind speeds will facilitate the dispersal of disease spores.
- Elevated CO_2 can enhance photosynthesis and reduce transpiration, resulting in increased yields and more efficient use of water. The responses are more pronounced in species possessing the C_3 mechanism than in C_4 and CAM[2] species due to the CO_2-concentrating mechanisms of the latter two groups. Plants show numerous other responses to CO_2, including changes in phenology, leaf anatomy and dark respiration, but it is unclear whether these are direct responses to CO_2 or indirectly reflect effects of increased carbohydrate levels or of decreased transpiration.
- Crop-simulation models are widely used to predict impacts of climate change on agricultural production. In regions where climatic conditions permit year-round cropping, however, changes in planting dates and crop durations may allow important adaptive changes in cropping patterns. The ability of simulation models

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[2] Crassulacean acid metabolism.

to predict how yield and phenology changes with planting dates make them highly suitable for examining temporal changes in crop sequences.

- The potential impacts of climate change on cropping patterns are highly researchable, but present significant methodological challenges. These impacts are not simply a question of increased or decreased productivity, but may have dramatic effects on land use as well as cropping practices. Ecological-niche modeling and crop-simulation modeling are powerful, complementary tools for examining the spatial and temporal aspects of climate-change impacts. Their successful application, however, requires effective interdisciplinary collaboration, including participation of plant biologists.
- Addressing the issue of climate change requires mitigation and adaptation. Mitigation implies either reducing emissions (by enhancing energy-production efficiency, and identifying low-C or no-C fuel sources) or sequestering emissions in long-lived pools (*e.g.* soil, biotic). Adaptation implies changing lifestyle and using technologies for management of resources in a manner that minimizes the adverse effects of climate change on soil and water resources.
- Crop yields increased by a factor of 3 to 5 during the second half of the twentieth century despite degradation of soil, desertification of land, and depletion/pollution of water resources. This quantum jump in yields and the overall increase in agronomic production was brought about by agricultural intensification through adoption of varieties that were responsive to fertilizer and irrigation inputs. However, future increases in irrigation, most likely to occur in Africa and South America, will exacerbate competition for water resources from rapidly increasing demands from non-agricultural (*e.g.* urban, industrial) uses.
- Demands for natural resources will increase drastically during the twenty-first century because of increased need for food/feed production, which may have to be doubled by 2050, and climate change which will further jeopardize the natural resources that are already under great stress. Adaptation to climate change will be essential for human well-being.
- When we think of the effects of climate change on future generations, needs for mitigation via lifestyle change and altered agricultural practice are clear. Predicted rises in sea level, destruction of traditional habitats and industries and loss of biodiversity push ethically acceptable climate policies strongly towards mitigation rather than adaptation.
- Important among several options for agricultural adaptation are choosing crop-management techniques including drought-tolerant (avoiding) and early-maturing varieties adopted in conjunction with adjustment in time of planting, and converting to farming/cropping systems that reduce risks and produce minimum assured returns in bad years rather than maximum production in good years, with focus on choice of appropriate species and diversification (mixed farming).

ETHICS, POLICY, CARBON CREDITS

- Ethics need to be distinguished from opinion. Surveys to determine what people think is right or wrong about climate change describe opinions rather than ethics. Too often, governments and industries make decisions based upon polls of people's opinions rather than on careful study of the ethical issues involved. Ethics is about *values* apart from people's opinions. Ethics assumes that some beliefs about right and wrong may be incorrect, and the study of ethics attempts to discover which are correct. In short, there is right and wrong above what people *think* is right and wrong, beyond people's opinions.
- Ethical decisions require that we combine scientific, social and economic facts relating to the threat of global climate change with general ethical principles that indicate right and wrong in all areas, and thus lead to specific policy recommendations.
- The Buddhist understanding of *karma* is that actions motivated by negative intentions tend to bring about adverse consequences, while actions motivated by good intentions tend to bring beneficial results. If our eagerness to develop and use transgenic animals is motivated by generosity, loving kindness and wisdom, which could include the mitigation of climate change, we can conclude that this technology is likely to bring good results. If, however, we are motivated by greed, ill will and delusion or ignorance, then we should expect this new technology to increase, rather than reduce, our suffering and frustration. This Buddhist approach does not imply that genetic engineering is bad in itself.
- In late 2009, the 15th Conference of the Parties under the Climate Convention will be convened in Copenhagen to address the directions laid out in the Bali Action Plan that countries agreed to in 2007 at the 13th Conference of the Parties. The Action Plan specified steps to be taken to "enable the full, effective and sustained implementation of the Convention through long-term cooperative action, now, up to and beyond 2012," which is after the end of the Kyoto Protocol commitment period. An agreed long-term global goal for emission reductions, to meet the Convention's objectives, is to be one outcome of the 15th Conference of the Parties, as well as interim targets. What those targets will be or even if there will be agreement on them, is uncertain. From an agriculture point of view, there will likely be important terminology, guidance and rules in the details. These details are even more difficult to predict.
- Designing adaptation policy for climate change will require, *inter alia*, assessments of the effectiveness, costs and feasibility of measures to reduce vulnerability; stakeholder analyses to identify targets and beneficiaries of adaptation interventions; and analyses of the consequences of inaction.
- As the climate changes, there will be stresses on agricultural production in some regions and opportunities in others. Will there be financial and regulatory sup-

port for diversification into other crops and for possibly relocating agriculture production to other areas? If so, in the latter case, will there be investments in public infrastructure, such as transportation and water supply, to support the new region?

- Production of the three main greenhouse gases—carbon dioxide, methane and nitrous oxide —can be mitigated through agricultural activities. Management practices can be altered or changed in many ways to reduce emissions, to enhance the removal of carbon dioxide from the atmosphere (C sequestration), or to displace emissions from fossil fuels by using crops or residues as sources of energy. Displacing fossil-fuel emissions with bioenergy from crops represents an important opportunity for agriculture and remains a fertile topic for research as governments continue to rely on renewable fuel standards as an important component of energy and climate-change policies.
- When evaluating a mitigation option, an important aspect is the distinction between the technical potential and the economic potential that an agricultural practice represents. Technical potential refers to the biophysical ability of a management practice to reduce emissions, but does not take into account its cost-effectiveness.
- The fact that science has demonstrated the potential for agriculture to provide emissions offsets under a cap-and-trade program and that including offsets as part of policy design may significantly decrease the cost of such programs is not enough to ensure the environmental integrity of legislation or international agreements that aim to mitigate the effects of climate change. The most substantive issues that must be addressed in order for agricultural offsets to be an effective component of a regulatory (non-voluntary) cap-and-trade program are verifiability, enforceability, additionality, and permanence.

PART II–BREAKOUT SESSIONS

Workshop Summary

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COLIN KALTENBACH
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Three breakout sessions were held at NABC 21, comprising a total of five workshops, at which the major issues raised during the plenary-session modules were enumerated and discussed. This is a synthesis of key points that emerged.

MODULE 1—CLIMATE CHANGE OVERVIEW AND PROJECTIONS

- Stakeholder engagement and education will be critical. (Stakeholders include policymakers, agricultural scientists, climate scientists, ecosystem-service providers, farmers, biotechnology industry personnel, economists and consumers.) All available means of communication regarding climate change effects on agriculture and food production need to be employed: extension agents, the Internet, "traditional" media and the scientific literature. In particular, scientists must reach out to policymakers.
- The need for such engagement and education is not limited to the subtleties of climate change, but includes the relatively more mundane aspects of production agriculture.
- Most politicians have a non-scientific background, making it critical that knowledge be communicated in ways that they understand.
- Most policymakers lack the knowledge-base to weigh the issues and the options.
- A complicating factor is the uncertainty inherent in available computer-simulation models. Improvements in these models must continue, with the objective of producing quantitative data.

    - On the other hand, it was suggested that the lack of precision is sometimes overstated, and more emphasis is needed on development of protocols for managing uncertainty. Some participants felt that there is too much emphasis on climate models and too little on decision-making protocols. Such protocols, as used in medicine, may have utility, underscoring the need for interdisciplinary effort.
    - Unequivocal data will help to address points raised by skeptical activists.
- Demand-side pull may be an important driver, including voluntary carbon cap-and-trade markets, green products and organic foods.
- With climate change, the frequency of extreme weather events will increase, with which risk-profiles will also change. The insurance industry will require accurate evaluations in order to price risk.
- Population increase must be factored into predictions of the results of climate change. Also important are improving living standards in China, India and elsewhere leading to dietary changes, in particular increased meat consumption.
- Emphasis is needed on optimizing efficiency of use of all inputs involved in production of food, fiber and biofuels.
    - Only with accurate life-cycle analyses of all input and output components can sustainability be achieved.

Module 2—Genetic Approaches to Crop Adaptation

- The roles and contributions of breeders and molecular biologists need to be examined and better integrated.
- Concern was expressed over the lack of availability of plant breeders. For example, not a single university in the UK provides training in traditional plant breeding. Non-molecular skills are being lost in other disciplines. (An encouraging note: Pioneer and Monsanto are funding university courses for training plant breeders.)
- The need for interdisciplinary teams begs the questions of how they should be created, and who will be the partners. Not only should industry, academia and government be involved, but input should be sought from farmers and consumers.
    - If farmers are paid for ecosystem services, they would be more amenable to adoption of appropriate new technologies.
    - Optimization of these various contributions would provide new justification for funding.
- Dynamic systems approaches are needed in making genetic improvements for resistance or avoidance of biotic and abiotic stresses that will become more severe with climate change.
- Major research efforts are needed to improve efficiency of water use and of photo-

synthesis; these important factors are linked.

- Means and funding are needed to analyze and identify useful traits in thousands of accessions held in plant-germplasm banks. Technology is available to characterize them genetically, but gaining understanding of their phenology will be problematic.

MODULE 3—OTHER APPROACHES TO ADAPTATION

- Depletion of carbon (*i.e.* organic matter) from soils—and concomitant loss of fertility—is an issue of major importance, particularly in view of the fact that soil has huge potential as a sink and reservoir for carbon. Tillage and other farm-management practices need to be modified so that organic matter is replenished and fertility—including water-holding capacity and nutrient retention—thus maintained or improved.
    - Removal of stover and straw as a feedstock for cellulosic ethanol production was questioned. If more nutrients are removed than put back, fertility will be lost.
    - On the other hand, biofuel production will continue to increase and must be integrated sustainably.
- Methods of soil-carbon monitoring need to be improved, and quantification of nitrous-oxide emissions made more precise. These factors are sensitive to even small fluctuations in temperature and soil moisture and will be affected by climate change.
- Soil microbiology must be part of the discussion.
- Moisture relations will be increasingly important as pressure on water resources increase and warming trends increase evapotranspiration. There is potential to breed for improved water-use efficiency in crops as well as for moisture-stress resistance and avoidance.
    - It will be important to understand and make allowances for how new policies related to climate change will affect other countries. Multinational engagement will be necessary. Judicious application of scientific knowledge is highly desirable.
- Ecosystem services and their sustenance are not adequately integrated into currently available computer-simulation models.
- More rigor is needed in predictive models as the basis for formulating strategic plans to justify new sources of funding.

MODULE 4—ETHICS, POLICY, CARBON CREDITS

- Profit taking and ethics are not necessarily mutually exclusive; it depends on the underlying motivation.

- Applying ethics to practical situations can be difficult for non-ethicists. Providing opinion must be viewed differently from weighing ethical considerations. Ethics are derived from principles and not from social mores.
- Unequal distribution of wealth is not necessarily unethical. Critical considerations are how we treat others, future generations, and plants and animals.
    - — Good examples are the Enviropig, produced for profit, which benefits the environment, and genetically engineered crops that will adjust to climate change.
- Moral and ethical issues are now represented by the media, the motivations of which may be questionable. Scientists need to take a stronger role and work with journalists.
    - — On the other hand, many scientists are poorly aware of ethical issues[1]. It was suggested that scientists should have ready access to ethics inputs, to guide their research. Similarly, teaching should incorporate ethical considerations.
- The science of mitigation of climate change is now being elucidated, but there has been little progress on the policy side.
    - — Since the scientific basis for policymaking has considerable uncertainty, it is recommended that policies be adaptable to accommodate improved data.
    - — To transfer science into policy will require engagement of politicians to ensure that their decisions are based on sound scientific data.
    - — Scientists and students should be taught how to give advice, not how to make policy.
- Cap and trade is the policy most embraced, but there is much to be said for a carbon tax.
    - — Cap and trade is being wrongly labeled as a tax.
    - — Incentives will achieve more than a tax.
    - — Sound scientific data must underpin the cases made for cap and trade and other policies under consideration.
- Interdisciplinary collaboration will be essential, requiring natural and social scientists of various kinds to work together.

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[1] For several years, NABC sponsored an annual Bioethics Institute to provide training for university faculty involved in genetic engineering. A similar institute may have utility, with emphasis on research to mitigate the effects of climate change.

PART III–PLENARY SESSIONS

Module 1: Climate Change Overview and Projections

Our Evolving Climate

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I will discuss our understanding of our climate system's recent past, projections for the future and the process leading towards the Fifth Assessment Report from the International Panel on Climate Change (IPCC). The IPCC has been in existence for 20 years, and has produced these reports at 5- to 6-year intervals. These documents are used globally to provide key pieces of evidence for policymakers. And I'll describe what's going on in the area for which I'm responsible in the preparation of the Fifth Assessment Report.

Unequivocal Warming

One of the key statements that came from the last report, published in 2007, is that warming of the climate is unequivocal. The evidence comes from air temperatures, from ocean temperatures—not just from the surface, but also from the body of the ocean—from reductions in the amounts of ice and snow on the surface of the planet, and from changes in sea level because additional water is being stored in the oceans and because the oceans are being warmed. Sea-surface temperature measurements are collected by ships primarily, but also by floats and robots. Although there is a great deal of natural internal variability in the system, we have strong evidence that human activity has been driving these temperatures upwards over the past 100 years.

Composition of the Atmosphere

If we look at the composition of the atmosphere over the past 10,000 years, we would see that something very rapid happened during the past 100 to 150 years in terms of concentrations of key greenhouse gases, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The natural variability of CO_2 concentrations—affected by comings and goings of the ice sheets—has been between about 180 and 280 parts per million (ppm), driven by changes in the Earth's orbital parameters. We understand this process well. But, over the past 100 years, the CO_2 concentration has risen by 100 ppm, more or less, above the natural upper limit. That CO_2 has come from our use of fossil fuels and of the land surface, causing movements of carbon from fossil and soil reservoirs into the atmosphere.

In the case of well mixed CO_2 and other greenhouse gases, of which the concentrations are more or less uniform over the surface of the earth, our understanding is high (Fig. 1). On the other hand, in the case of ozone, also a greenhouse gas, our level of understanding is less. Increases in ozone concentrations near the Earth's surface occur, not because we are releasing it but because of other compounds that we are releasing from which atmospheric photochemistry produces ozone as a byproduct. In the stratosphere, manmade ozone interacts with other compounds, lowering the ozone concentration with a small offsetting cooling effect.

Another aspect under discussion is the role of black carbon (Fig. 1)—produced by smokestacks, diesel engines, *etc*.—which decreases the reflectivity of snow, ice and other bright surfaces, causing them to convert more of the incoming sunlight to heat and accelerating the melting of those surfaces. Locally this may significantly affect climate change, although globally it is estimated not to have a huge affect, at least not as described in the current IPCC report.

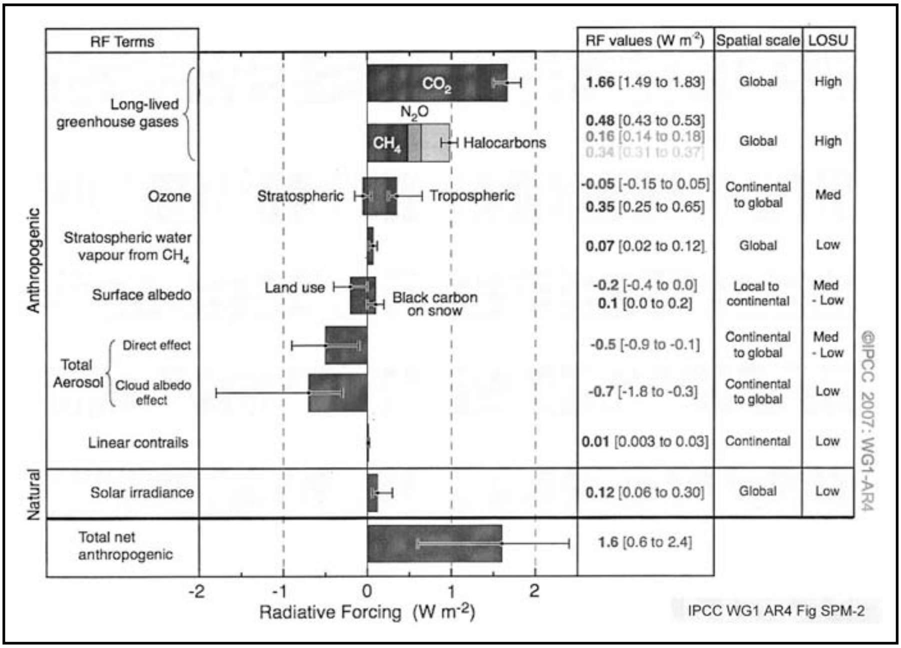

Figure 1. Radiative forcing components (1750–2005).

An area of which we know relatively little has to do with the direct and indirect effects of aerosols that we emit into the atmosphere (Fig. 1). For example, sulfur dioxide from smokestacks is quickly converted to sulfate, which coalesces into droplets. Those droplets reflect incoming sunlight back to space so that less of the sun's energy warms the Earth's surface, which has a cooling effect. These aerosol particles are also thought to have an indirect effect as cloud-condensation nuclei (Fig.1). If there are more of these nuclei around but not more water, the effect is to produce clouds with larger numbers of smaller water droplets, which makes those clouds brighter. Brighter clouds are more reflective and might also be longer-lived. Thus, a cloud of a certain reflectance that exists for a longer period of time, would, of course, have a greater cooling effect on climate. However, in this case, the level of scientific understanding is still quite low.

Forcing Factors

Overall, we can say that the total net anthropogenic effect has been positive since the Industrial Revolution (Fig. 1). One of the ways in which we figure out whether or not these changes are affecting climate is by building computer-simulation models, which we run with the known history of changes in atmospheric composition including concentrations of CO_2 and other long-lived greenhouse gases, occurrence of volcanic events and estimates of change of solar output over time. Accordingly, we can do a pretty good job of reproducing the history of the twentieth century on a global scale by taking into account the effects of human *and* natural external factors on the climate system (Fig. 2a). If we leave out the human factors and include only the natural factors—solar and volcanic forcing—then we cannot explain the rapid warming that occurred during the latter part of the century (Fig. 2b).

The same exercise is possible on smaller scales. However, with respect to Alaska, central North America, eastern North America or Greenland, there is more variability. In the latter part of the twentieth century, divergence between climate-change simulations that include anthropogenic forcing and those that do not is less clear, because, on the smaller scale, it is more difficult to separate forcing effects from internal variability. Nevertheless, the available models are able to provide better explanation of what has happened when anthropogenic forcing is invoked.

We have a pretty strong understanding of what has driven, at least, temperature change over the past 100 years. And I would argue that we have reasonably strong understanding what has driven temperature change on much longer timescales than that.

Projections

Computer simulations of future events use various scenarios for changing greenhouse-gas composition, changing aerosol composition in the atmosphere and so on, over time. For example, we asked the question, "If the CO_2 concentration were to remain constant at the year-2000 level for the following 100 years, what would the eventual warming be?" Models indicate that surface-temperature warming would be approximately 0.1°C per century, which would eventually taper off; in other words, it would take a few centuries for the surface temperature to stabilize at a new level. Ocean temperature or sea-level rise would take a much longer period of time to stabilize.

A certain amount of change is inevitable because the climate system is not at equilibrium with the rate of forcing that it is receiving. If we think of the climate system as a pot of water, almost all of that water is in the ocean and if we set that pot on a stove and turn the burner on a little, eventually it will come to a new steady temperature.

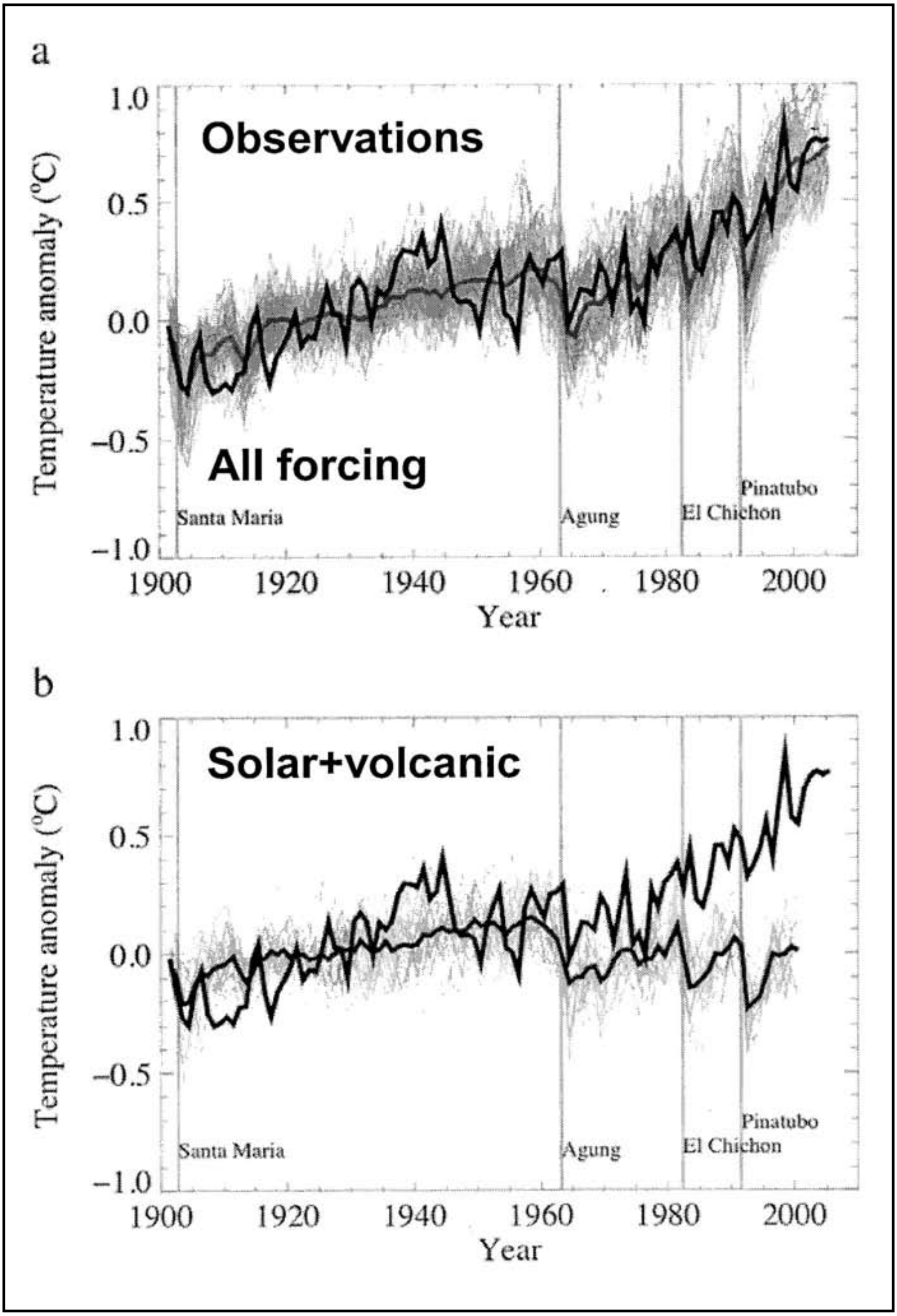

Figure 2. The relative effects of human and external factors on global temperature.

The climate model is essentially a low-resolution weather-forecasting model. The statistics of the variability that climate models produce are similar to the statistics of the variability that we experience in the weather. Medical science learns a lot about humans by studying pigs, and the distance between a climate model and the real system is like that proxy for the human organism compared to ourselves.

The spatial patterns of change predicted by various models are similar because they are determined by where the land is and by what the feedback processes are. These feedback processes are operative at all times, both at low levels of forcing and at high levels of forcing. Therefore, the intensity of these patterns changes but not their specific shape.

Comparing projected precipitation changes of several models occurring when CO_2 atmospheric concentration reaches 750 ppm reveals significant disagreement as to magnitude of change, but better agreement in terms of the sign of the change (*i.e.* whether positive or negative). Comparing projections for North America for summer and winter, it is expected that winters will be wetter and summers will be not only be warmer but also drier, which translates into more crop stress during the growing season.

The IPCC regional diagrams report similar results for annual mean winter and summer temperatures. At the end of the twenty-first century, we expect annual mean warming in North American on the order of 4 degrees, with annual mean moistening but primarily in winter, and drying in summer.

Weather Extremes

One key impact area has to do with precipitation extremes. When I lived in Saskatoon, I learned of the local concern over convective precipitation in summer, and its effects on cars as well as on crops. After a hailstorm we had to return our new vehicle to the dealer to have the dimples taken out.

Figure 3 shows a Canadian climate model, but every similar model would produce a similar diagram. It shows the model's ability to simulate intense precipitation events for the current climate, labeled "1990," averaged over the temperate part of North America. It predicts that a 10-year event would be a 50-mm rainfall within 24 h and a 100-year event would produce approximately 70 mm of precipitation. We know from analyzing the record that the latter is relatively small; however, that is to be expected because the climate models don't have individual convective cells occurring within grid boxes that are removing moisture from layers of air and depositing it on the ground uniformly over large areas such as 100×100 km or 200×200 km. Therefore, we would expect the simulated extremes to be smaller. If you take the 100-year event as simulated by this model and ask how frequently that event will occur towards the middle of the twenty-first century, the answer is about once every 70 or 75 years. And towards the end of the twenty-first century, that event will occur approximately every 50 years. If a storm sewer system is designed to deal with a 100-year event, it means that basement flooding, *etc.*, will occur approximately once per century. Similar flooding may occur every 50 years at some point in the future.

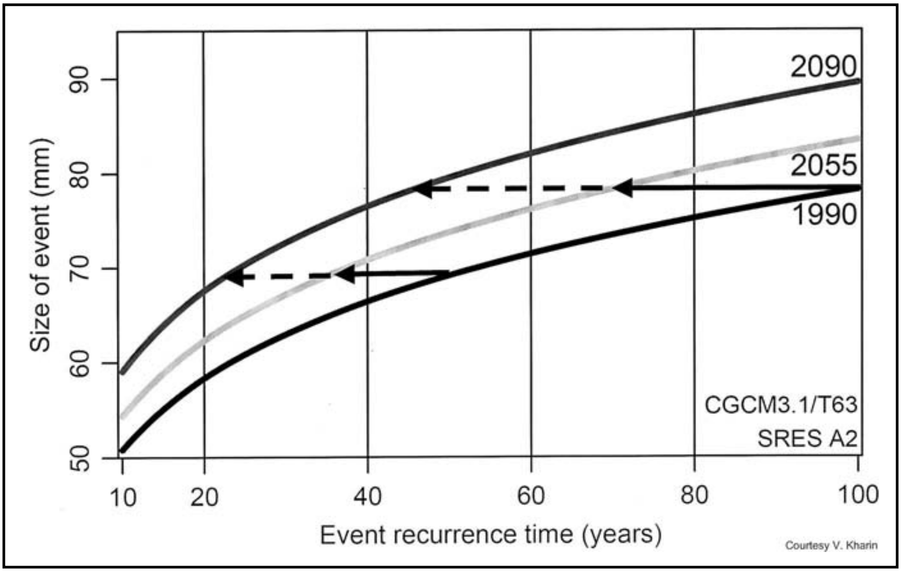

Figure 3. Predictions of 24-h precipitation extremes for North America (25–65°N).

New Forcing Scenario

The IPCC's Fifth Assessment Report will include a new type of forcing scenario called a representative concentration pathway (RCP), which we will provide to models as a prescription for how greenhouse-gas concentrations will change over time, leading to particular levels of forcing at stabilization. As there has been for previous IPCC reports, an international committee is organizing the climate modeling community to run with these new forcing scenarios. Planning for that is well underway and some modeling groups are ready to run with these new forcing scenarios if the experiment includes an attempt to probe the ability of climate models to make CATO predictions—which would be of interest to this community, to be able to plan on the CATO timescale how to undertake changes in hedging behavior, for example, and then also long-term projections for formulation of mitigation policy. These RCP scenarios are aimed at climate models that have active carbon cycles, specifying that there is a certain amount of CO_2 in the atmosphere at a particular period of time, such as 450 ppm in 2050. There will have been a certain pathway to get there, which means that the climate system will have responded with warming and changes in precipitation distribution, with corresponding changes in vegetation because these models will have active terrestrial ecosystems. Responding to the physical and biogeochemical state of the system, the climate model will try to draw CO_2 out of the atmosphere and reduce the 450 ppm. However, the 450 ppm is specified, meaning that there must have been emissions from us, so, by saying what path we are on, we are asking the climate model what emissions are allowed in order to stay on that path. The plan will include a forcing scenario where we actually get to a negative emission scenario by deploying technology that allows us to remove carbon from the atmosphere and sequester it.

SCIENCE INFORMING MITIGATION POLICY

Figure 4a shows how atmospheric CO_2 concentration varies with latitude and over time, in this case from 1992 to 2001. The rear of the diagram shows CO_2 concentrations near the North Pole at which there is a strong annual cycle. Plants take up lots of carbon in the summer, and the biosphere gives up lots of carbon to the atmosphere in the fall and winter. The annual cycle is reversed in the southern hemisphere, and it's weaker because there is relatively little land there and more ocean, which has a much less-pronounced annual cycle. The general level of CO_2 is increasing over time, which is the part that concerns us, of course, and requires mitigation.

Figure 4b shows our current capability to model this in Canada. It's a global climate model with terrestrial- and ocean-ecosystem components. We told the model what the emissions were during the twentieth century and it is calculating concentrations, tucking carbon away in the right places and producing annual cycles and a general trend that is close to observed. In fact if we start in 1850 with the concentrations as they were then and add what the emissions have been over time, the model correctly produces the year-2000 concentrations. We are making progress here.

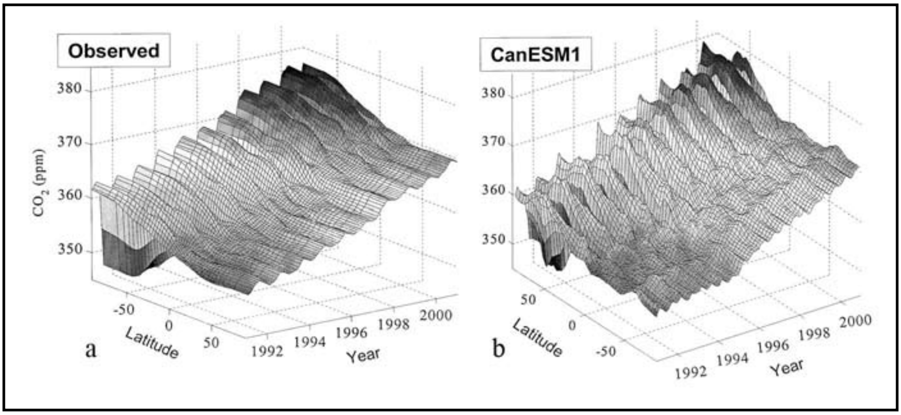

Figure 4. Zonal mean CO_2 concentrations (1992–2001).

CURRENT EMPHASES

We are also making progress in our ability on shorter time scales. Operating in research mode, we have a coupled atmosphere ocean cryosphere system where we can initialize the ocean from a particular state at a particular point in time and then forecast ahead in time just like making weather forecasts.

We are also developing a new regional climate model for Canada, which is needed to get down to smaller scales that are key for understanding impacts and working out adaptation scenarios. This regional climate model is operated out of Montreal by a consortium, "Ouranos," that is producing continent-scale climate-change simulations. The technology that we use for that is becoming old. In the short term, it will continue to run on computers that are available in Montreal; however, the computing architecture available today is incompatible with how this particular model is constructed, so we are involved in a project to build a new regional climate model for Canada that uses a technology for solving the equations of motion that is amenable to the massively parallel types of machines available today. We are now driving this regional climate model with observations at the moment and will apply it to climate change projections over the next couple of years.

Conclusions

The Fourth Assessment Report, I would argue, tells a compelling story about the causes of past climate change. It provides more clarity and greater policy relevance than previous reports. Furthermore, the language used to relate cause and effect is changing. The Second Report, published in 1996, stated, "The balance of evidence suggests a discernable human influence," so perhaps a little bit better than 50/50. In the Third Assessment Report in 2001, we said, "There is new and stronger evidence that most of the warming of the past 50 years is likely attributable to human activities." "Likely" is a coded word in IPCC parlance, meaning that there is one chance in three that the statement is incorrect, and two chances in three that it is correct. In 2007, a great deal more science was available, with much better understanding of processes. And, of course more data were available. The signal had emerged more strongly and the net effect on the report was that we upgraded "likely" to "very likely," which means that our assessment is that the statement is correct with a probability greater than 0.9, *i.e.* less than one chance in ten that we are pointing at the wrong thing, and likely a much smaller chance than one chance in ten. It's a pretty conservative process.

The Working Group 1 Report that made this statement went through four reviews, which were open to anyone who wished to call her/himself an expert. People on all sides of the debate were able to comment and criticize. Some 30,000 comments were submitted and within the IPCC we developed a process for tracking them. Each comment was recorded. The author teams recorded how they responded to each of those comments, and that dialog is available as part of the public record. Review editors looked over our shoulders to ensure that we were dealing with comments appropriately and in an equitable fashion.

Future changes are inevitable. That means we will need to adapt and need to mitigate and that's a focus of current discussion. Planning of the Fifth Assessment Report is well underway. The scoping meeting for that report will take place in about a month. The new forcing scenarios will be a challenge, but will provide us with opportunities to do more science. There are dual objectives both to inform adaptation on shorter time scales and to inform mitigation on longer time scales. The timeline for getting all this right, and producing a new set of reports, is very tight. Regionalization is going to be a big issue and difficult for us to deal with. However, in Canada we are in pretty good shape in terms of tools to run for the Fifth Assessment Report.

FRANCIS ZWIERS is an internationally recognized expert in the fields of climate-change detection and attribution, the analysis of climate variability and extremes, and in climate modelling and analysis. He was recently elected to the bureau of the Intergovernmental Panel on Climate Change (IPCC), an organization with which he has been involved since its inception, including as a coordinating lead author of the chapter "Understanding and Attributing Climate Change" in the most recent IPCC Assessment Report.

Dr. Zwiers served for a decade as chief of Canada's premier climate modeling centre, the Canadian Centre for Climate Modelling and Analysis, and, since 2006, he has directed the Climate Research Division within Environment Canada.

He is a fellow of the Royal Society of Canada and has received numerous awards and accolades for scientific excellence and distinguished service.

The Impact of Agriculture on Climate Change

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In considering the role of agriculture with respect to climate change, it is important to consider the impact of agricultural practices on the microclimate. For example, the type of vegetation, method of tillage, amount of land cover, type of windbreak and type of irrigation system are all factors that influence the microclimate and macroclimate either directly or indirectly, whether by changing transpiration, particles in the air (dust, soot), precipitation, wind, *etc*. These changes can alter the global climate if the energy budget at the Earth's surface is significantly changed. The main source of energy at the Earth's surface is the incoming solar radiation. However, as can be seen in Fig. 1, there is a whole series of forcing agents that have the potential to affect the radiation budget and the Earth's temperature. Some forcing agents, such as greenhouse gases (GHGs), cause warming whereas others, such as increased reflectivity of the surface (albedo) and aerosols, mainly cause cooling.

Globally, agriculture accounts for 13% of the radiative forcing related to GHGs; in Canada and the United States it accounts for 6% to 8%. The GHG emissions in Canada and the United States are mainly in the form of methane (CH_4) and nitrous oxide (N_2O) (IPCC, 2007). Agricultural sources such as animal husbandry, manure management and agricultural soils account for about 52% of global methane (CH_4) and 84% of global nitrous oxide (N_2O) emissions (Smith *et al.*, 2008). In the past, deforestation and intensive agriculture (*e.g.*, cultivating grasslands) have contributed significantly to the increase in atmospheric carbon dioxide (CO_2). For example, until the 1970s, more CO_2 had been released into the atmosphere from agricultural activities than from fossil-fuel burning (Lal *et al.*, 1998).

Agricultural activities can influence climate through land-use change, which can modify the albedo of the Earth's surface. The albedo (α) in an agricultural context depends on a variety of factors including crop type (*e.g.*, cereals, forages, broadleaf crops, shrubs, bare soil), crop phenology (seedlings to mature plants), management practice (tilled, fallow, fertilized), surface condition (wet or dry), time of day (solar elevation) and time of year (growing season or snow cover). Any combination of factors that result in an increased albedo means that less solar energy is absorbed by the Earth's surface. Compared to the globally averaged albedo of about 0.3 for the Earth's surface (Bender *et al.*, 2006), land covers with higher albedo (such as deserts, snow and ice, α = 0.35 to 0.90) tend to lower the air temperature, whereas land covers with lower albedo (such as oceans, grasslands and forests, α = 0.05 to 0.20) tend to increase air temperature. Based on the global annual average incoming shortwave radiation of about 341 Wm^{-2} (Trenberth *et al.*, 2009), a decrease of 0.005 in global albedo would modify the shortwave radiation forcing by about 1.7 Wm^{-2} and cause an increase in the global air temperature by about 0.9°C (Cess, 1976).

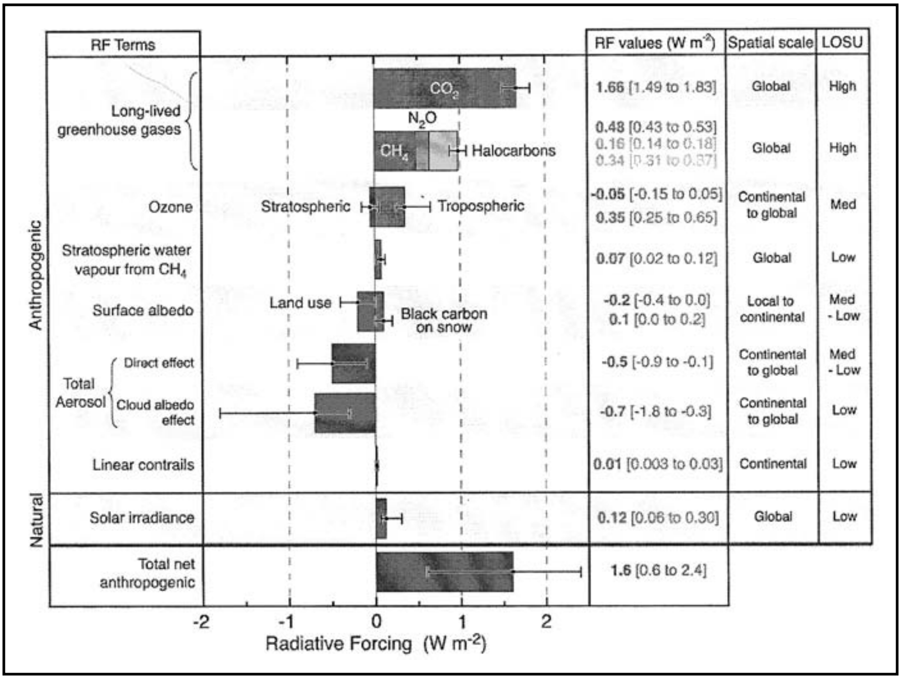

Figure 1. Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic CO_2, CH_4, N_2O and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU) (IPCC, (2007).

Agriculture also impacts other radiative and non-radiative forcing agents that can have either a direct or an indirect effect on the climate (IPCC, 2007). As can be seen in Fig. 1, aerosols that are abundant in the environment as dust particles (from bare soil and plant residues) or as anthropogenic residues of combustion (from crop burning) can have a significant cooling effect. They have a direct effect on the radiation budget by scattering and absorbing short-wave and long-wave radiation. They also have an indirect radiative effect by influencing cloud formation, which may then lead to changes in the incoming solar radiation. An example of non-radiative forcing is a change in the hydrological cycle due to different soil and crop conditions. This can modify the surface fluxes of heat and moisture, thereby changing the lower boundary conditions of the atmosphere, and influencing weather and climate (Pielke *et al.*, 1998).

Agriculture plays a relatively important role with respect to climate change, primarily because rapid changes in land use result in concomitant changes in the environment (Goldewijk, 2004). For example, the global area of cropland increased from 265 Mha in 1700 to 1,471 Mha in 1990 while the area used for grazing livestock increased from 524 Mha to 3,451 Mha. My objective is to examine the magnitude of the past, present and future impacts of agriculture on climate change and to discuss the possible tradeoffs between biogeochemical and biogeophysical forcing agents associated with management practices to minimize any negative impact of climate change.

Impact of agriculture on past climate

Anomalies in the concentration patterns of CO_2 and CH_4 during the last 8,000 years have helped demonstrate the role of the development of agriculture on climate change. Ruddiman (2003) reported an anomalous increase of about 40 ppmv in CO_2 during that period, which he hypothesized was related to forest clearing for the development of agriculture in Europe and China, which began 8,000 years ago. He also attributed an upward deviation of up to 250 ppbv in CH_4, observed during the last 5,000 years, to the adoption of paddy rice farming in Asia. He estimated that the increase in the atmospheric concentration of these gases increased global air temperature by about 0.8°C. He also suggested that several CO_2 oscillations of about 10 ppmv in the last 1,000 years were likely due to farm abandonment in western Eurasia due to bubonic plague, resulting in forest regrowth.

On an annual basis, early agricultural systems contributed little to the GHG build up in the atmosphere because of the small populations; however, small contributions integrated over long periods of time can become significant. For instance, land clearance for agriculture is estimated to have been a major source of CO_2. Between 8,000 years and 200 years ago, CO_2 emissions from land clearance were estimated to be about 0.04 Gt C yr^{-1}, for a total of about 310 Gt C. Since the industrial revolution in 1800, CO_2 emission from land clearance has averaged 0.8 Gt C yr^{-1} for a total of about 160 Gt C. Therefore, the small annual CO_2 emissions prior to the industrial revolution contributed about two times more CO_2 than the post-industrial revolution emissions (Ruddiman, 2003).

Using results from computer simulations, Betts *et al.* (2007) demonstrated that historical deforestation of predominantly northern temperate regions, with their snow cover during winter, probably did not contribute to global warming, if the effect on temperature due to the increase in albedo from land use change is taken into account. They showed that, by 1950, the global mean radiative forcing decreased by 0.18 Wm^{-2} as natural land cover was converted to agriculture and that winter and spring temperatures in northern temperate regions are probably 1 to 2°C cooler as compared to the temperature they would have been if land clearance had not occurred. They also estimated a decrease in radiative forcing from 1950 to 1990 of -0.06 Wm^{-2}, which may be associated with the Green Revolution in Asia.

IMPACT OF AGRICULTURE ON PRESENT CLIMATE

In the past 20 years, about 75% of the CO_2 emissions have been attributed to fossil-fuel burning and the remainder to land-use change (IPCC, 2001). The major impacts of agricultural land-use change are occurring in tropical rainforest regions such as Brazil, Congo, and Indonesia where native rainforests are being cleared for cultivation and pasture. Tropical deforestation, which now exceeds 13 Mha per year (World Resource Institute, 2000), is a substantial source of CO_2. It also causes a moderate increase in albedo, which causes cooling of the air; however, this cooling is more than offset by a warming of the air through a reduction in evapotranspiration and through CO_2 emissions associated with deforestation.

Through agricultural activities (*e.g.*, land clearing, cultivation of annual crops, irrigation, grazing of domesticated animals), humans are extensively altering the local, national and global land-cover characteristics, including physiological and physical characteristics. It is generally accepted that the expansion of agriculture into natural ecosystems has had a significant climate impact. Lobell *et al.* (2006) used the National Center for Atmospheric Research (NCAR) general circulation model to demonstrate that a reduction in tillage can have a significant cooling effect by increasing the albedo. The NCAR model predicted that increases in soil albedo by reduced tillage have a potential global cooling effect of 0.2°C. This value is comparable to the biogeochemical cooling from the expected global soil carbon sequestration potential. Boucher *et al.* (2004) examined the human influence of irrigation on atmospheric water vapor and climate. They estimated a global mean radiative forcing in the range of 0.03 to 0.1 Wm^{-2} due to the increase in water vapor in the atmosphere, but a cooling of up to 0.8°C over irrigated areas.

Summer fallowing, which is the practice of leaving land unplanted for a whole year to conserve soil moisture and control weeds in semiarid environments such as the Northern Great Plains, is now much less prevalent in Western Canada and the United States than it was prior to 1975. The area of land left fallow in Canada increased from 8.7 Mha in 1951 to 11.4 in 1975, however with alternatives to summer fallowing, such as snow trapping, irrigation, mechanical or chemical weed control and cultivars that make more efficient use of water, a reduction to 5.4 Mha had occurred by 2001. Associated with this change, for the period between June 15 and July 15, Gameda *et al.* (2007) reported an increase of about 2°C between 1951 and 1975 in the mean air temperature of all soil zones in the prairies, where summer fallowing was practiced, then a decrease of about 2°C for the period between 1976 to 2001 (Fig. 2a, b). They also reported an increase in precipitation of about 20 mm from 1976 to 2001. This is because the flux of heat is less over cropped land than over bare soil, whereas evapotranspiration is greater over cropped land as compared to bare soil, which adds moisture to the atmosphere. Therefore, conversion of land from summer fallow to crops decreases air temperature and increases the water content of the air, potentially resulting in greater precipitation. Several authors have documented that regional evapotranspiration by agricultural crops is an important source of moisture for growing-season rainfall (Brubaker *et al.*, 1993; Trenberth, 1999). Summer fallowing tends to enhance decomposition of crop residues as the result of greater soil temperature and soil moisture as compared to cropped soils. Therefore, soils that are frequently under summer fallow have C contents that are several tons per hectare less than those that are cropped continuously.

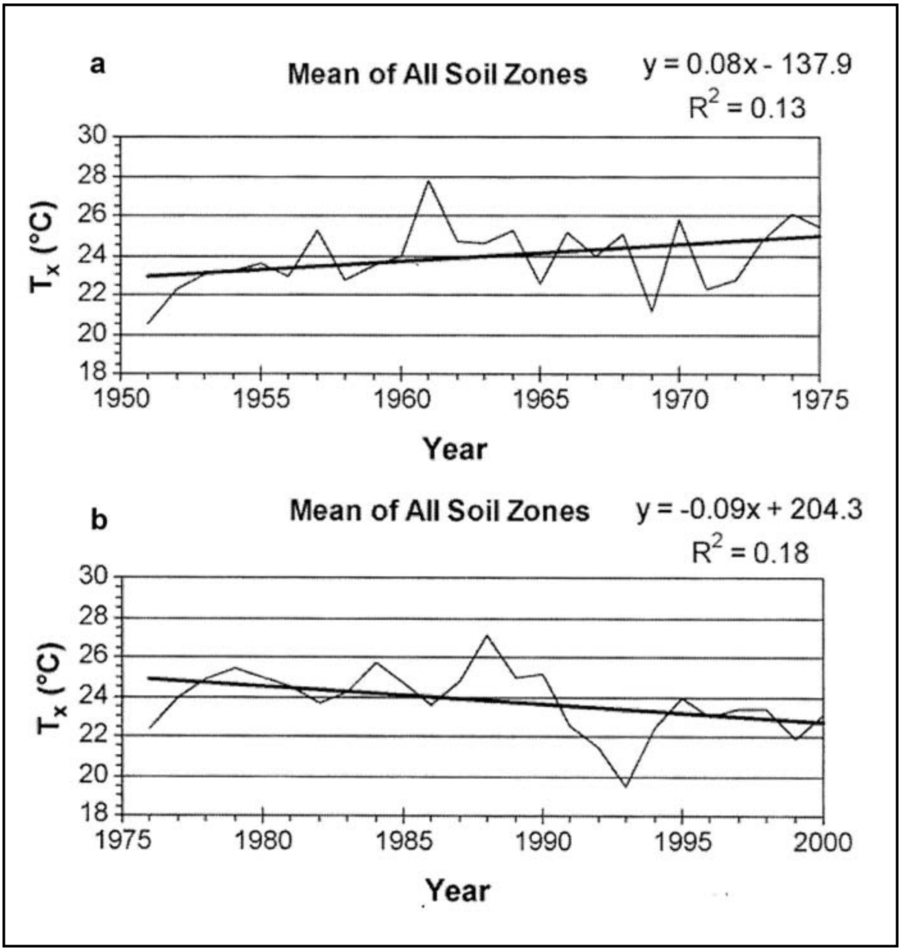

Figure 2. Trends in mean daily maximum temperature for the period June 15 to July 15, between a) 1951 and 1975 when area under summer fallow increased, and b) 1976 and 2001 when the area under summer fallow declined on the Canadian prairies (Gameda *et al.*, 2007).

By converting summer fallow to wheat in western Canada, carbon can be sequestered in soils at a rate of about 100 kg C ha^{-1} yr^{-1} (Campbell *et al.*, 2005). The biogeophysical effect of reducing summer fallow complements the effect of increasing C sequestration.

The biogeochemical and biogeophysical impacts of GHG-mitigation strategies on climate are not always complementary. For instance in Canada, afforestation and reforestation of marginal agricultural lands have been suggested as strategies to mitigate climate change by sequestering C in forests. However, planting trees, particularly conifers, on agricultural land in northern regions may result in more radiation being absorbed and thus increase temperature, thereby negating the beneficial impact of C sequestration. That is, the biogeophysical effect of land-use change is likely more significant than the biogeochemical effect in terms of climate change. To illustrate this point, consider the conversion of 1 ha of wheat to coniferous forest, which would result in the sequestration of approximately 60 t of C over a 50-year period, which is equivalent to a global radiative forcing of -0.20 nWm^{-2} (Betts, 2000). However, the negative radiative forcing of this hectare of land is completely offset by the biogeophysical forcing of -14 Wm^{-2} (AK Betts *et al.*, 2007), which is equivalent to 0.27 nWm^{-2} on a global scale, resulting in a net positive forcing of 0.07 nWm^{-2}. This example demonstrates that GHG-mitigation practices, such as reforestation of agricultural lands need to account for both the biogeochemical and biogeophysical forcings.

There has been substantial progress in agriculture in recent years in reducing GHG-emission intensities, that is, emissions per unit of product. For example over the last 20 years, a significant reduction in GHG-emission intensities has been reported for the major livestock industries in Canada (Dyer *et al.*, 2008; Vergé *et al.*, 2008, 2009). The improvements in GHG-emission intensities have been realized because of a combination of improved animal breeding, reduction in tillage intensity and a reduction in synthetic fertilizer use as the result of increased feeding of leguminous crops. Combined, these factors have increased milk-production efficiency by 35%, beef-production efficiency by 37% and pork-production efficiency by 23%. Despite the improvements in GHG emission per unit of product, because of the increasing demand for food over this time period, animal production has increased substantially and total GHG emissions have continued to increase, hence this progress has not helped agriculture reduce its impact on the environment.

Potential impact of agriculture on future climate

There are approximately 1.4 billion hectares of farmland in the world today (FAO, 2003). Currently, the potential for further expansion of agricultural lands is limited because most of the good-quality arable land is already under cultivation. There is some limited potential to expand agricultural lands in humid tropical regions (FAO, 2003), but these areas have major limitations due to steep slope, stoniness, soil depth and poor natural fertility. With increasing population, agricultural lands are likely to come under increasing pressure. Emerging carbon-credit markets and biofuel incentives may encourage producers to intensify agricultural practices to enhance productivity. Some expansion is then likely to occur onto marginal land. This is likely to lead to land degradation and, in some instances, desertification. Land degradation has already taken place in many regions of the world because of dramatic changes in agricultural practices during the last several decades (Sivakumar, 2007). The obvious impact of land degradation is an increase in surface temperature and a decrease in latent heat flux, but actual changes are much more complex. The impacts affect regional atmospheric circulation far beyond the region involved (Werth and Avissar, 2002).

In agriculture, the main option for mitigating climate change is still considered to be the sequestration of C in soils. Agricultural management practices such as reduced tillage, converting cropland to forage crops, permanent cover crops, fall-seeded crops, better crop cultivars, more efficient use of nutrients, optimized irrigation, reduced summer fallow, more chemical fallow and leaving tall stubble standing to reduce evaporation and trap snow have all been identified as beneficial for increasing C sequestration and/or reducing GHG emissions. It is estimated that, globally, agricultural soils could be a potential sink of 30 to 60 Pg C over the next century (Lal, 2003). This is the case because soil-C stocks have been considerably depleted by farming. In Canada, it has been estimated that agricultural soils have lost about 1,000 Tg C since cultivation began (Smith *et al.*, 2000). The potential then exists to sequester in agricultural soils some of the CO_2 released by fossil-fuel combustion (Boehm *et al.*, 2004), however, even this potential is threatened by climate change. Using the Century Model (Parton *et al.*, 1993), Smith *et al.* (2009) predicted that by 2100, agricultural soils would lose between 62 and 164 Tg C, depending on the climate scenario. Because of the lack of permanence of soil C sink, there is a need to search for lower risk options to store CO_2.

We need to examine all reasonable strategies for climate-change mitigation in order to predict future climate. Many examples have been mentioned in the literature, but few have been fully studied (Table 1). For example, the production of biomass for biofuel production is frequently presented as a promising option to reduce net GHG emissions (Farrell *et al.*, 2006).

TABLE 1. THE IMPACT OF VARIOUS AGRICULTURAL PRACTICES ON CLIMATE CHANGE.

Agricultural practice	**Biogeophysical effect**	**Biochemical effect**	**Net effect**
Reduced tillage	–[a]	––	––
Reforestation	+++	––	+
Deforestation	––	+	–
Plant forage crops	–	––	––
Irrigation	–	–+	–
Biochar	+	––	–
Leaf albedo bioengineering	–	–	––
Biofuel	–	–+	–
Reduced meat consumption	+	––	–
Reduced fallow	–	––	–––
Plant fall crops	–	–	––
Leave long stubble for snow trapping	–	–	––

[a] + indicates warming; – indicates cooling

The application of biomass-derived black C (biochar) to soil has been proposed as a novel approach to establish a significant long-term sink in terrestrial ecosystems (Lehmann, 2007). Others have proposed that tackling regional climate change using a "bio-geoengineering" approach, using crop cultivars specifically chosen to maximize solar reflectivity, could result in a summertime cooling of more than 1°C throughout central North America and mid-latitude Eurasia (Ridgewell *et al.*, 2009). Stehfest *et al.* (2009) have reported that changing human diet, specifically less consumption of meat, could significantly impact climate change by reducing methane emissions. Feddema *et al.* (2005) demonstrated the importance of including land-cover change in forcing scenarios for future climate studies. For example, they estimated that reforestation in western Russia would lead to warming. One of our challenges for the future is to improve the information in Table 1 and make the information quantitative rather than qualitative.

Discussion and Concluding Remarks

There seems to be little doubt that climate change is occurring. The impact of agriculture on climate change is not fully understood, but it is clear that the human role within the climate system is considerably more than the increase in GHG concentration (Pielke Sr. *et al.*, 2007). Because agroecosystems are intensively managed, as farming practices evolve the role of agriculture will undoubtedly change. We have shown several examples of the diversity of human climate forcing. Agricultural practices can influence climate through a modification of the surface energy budget (the biogeophysical effects), as well as through GHG emissions (the biogeochemical effects). Many programs have been initiated to mitigate GHG emissions and, so far, considerable progress has been reported in reducing the GHG-emission intensities from agricultural sources, but because of increasing food demand and increasing energy requirements, the total GHG emissions from agriculture keep increasing. Biofuels hold some promise for reducing our dependency on oil and gas, however, at this point, it is still not clear if the net GHG saving gained by replacing a fossil fuel with biofuel options such as corn ethanol, soybean biodiesel or simply crop-residue-generated biofuel will appreciably reduce GHG emissions. So far, mitigation measures have been biased towards minimizing the biogeochemical effects, but there is growing awareness that the biogeophysical effects may also be important and should be considered in designing policy intended to mitigate climate change. Linking carbon storage in agroecosystems with other climate-forcing agents is the most reasonable approach for developing policies that maximize the impact of agroecosystems in climate policy. Better information on the various types of forcing is particularly important to help decisions that people, governments and industries of the world will have to make to minimize the impact and the consequences of climate change.

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Dr. Desjardins is acknowledged worldwide for having developed original techniques to measure carbon dioxide and various trace gases using tower and aircraft-based systems. He has been the principal investigator in many NASA-funded large-scale experiments designed to improve the understanding of biosphere-atmosphere interactions. He leads a research program on quantifying and reducing greenhouse-gas emissions, ammonia and particulate matter from agricultural sources.

Desjardins serves as a member of the editorial board of the *Journal of Agriculture and Forest Meteorology* and is a fellow of the Canadian Society of Agricultural Meteorology, of the American Society of Agronomy and of the Agricultural Institute of Canada. He represents Canada on the Commission of Agricultural Meteorology of the World Meteorological Organization and has led many national programs in agricultural meteorology. Recently, he served as leader of an international-expert team on the contribution of agriculture to climate systems for the World Meteorological Organization.

He has authored over 200 refereed publications and edited several books.

The Impacts of Climate Change on Agriculture in North America

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I will restrict my comments to issues affecting North America rather than detailing what we know and don't know about climate change and agriculture. I'll discuss some results from the Intergovernmental Panel on Climate Change (IPCC) as a stage setter, and then talk about a couple of assessments from the United States. I'll also provide information on assessments from Canada and discuss issues that are important for thinking about the impacts on agriculture, including uncertainties about the carbon-dioxide (CO_2) fertilization effect and effects of extreme events on crops. I will say a little bit about a couple of issues in adaptation that are important.

Intergovernmental Panel on Climate Change

I'll start with statements relating to agriculture in North America from the Fourth Assessment Report of the IPCC:

- Research since the Third Assessment Report supports the conclusion that moderate climate change will likely—and "likely" means something fairly specific in IPCC parlance[1]—increase yields of North American rain-fed agriculture, but less so than projected in the 2001 report and with more spatial variability.
- Most studies project climate-related yield increases of between 5 and 20% over the first decades of the twenty-first century with overall positive effects persisting through the latter half of the century.

Sounds good. What's the problem? For one thing, these are generalizations and, although the IPCC Report does have a lot of great information in it and has been thoroughly reviewed, opinions differ about how optimistic we should be about agriculture and about what spatial scale is applicable. It's one thing to say that all will be well globally,

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[1] See page 26.

but it's another thing to say what's going to happen to a particular farmer in southern Saskatchewan, for example.

I won't deal with tropical agriculture in detail, but many studies indicate that the positive effects of climate change will be less marked in the tropics than in temperate agriculture. One of the conclusions of the Fourth Report and others is that, in the tropics, we will see yield losses even with small changes in temperature.

FARMERS' OPTIONS

Let's look at wheat, which is important to large swaths of North America. At least two options are open to farmers in adapting to climate change to maximize benefits from thermal resources: change the planting date and/or the variety. Sometimes increased irrigation is also an option. For a 1 or 1.5°C increase, we could see yield increases. But it's noteworthy that there is a great deal of scatter in these results. It's important for us at this conference, specifically, to address these uncertainties because they end up making a big difference in terms of how we potentially adapt.

A 2004 government report summarizing climate-change issues for Canada is applicable to most temperate regions. One of those issues is increased insect infestation of crops. Others are increased weed growth and disease. Studies now are in progress to elucidate the effects of competing weeds and diseases as well as insects. In Canada, increased productivity may be expected from warmer temperatures, especially if the winter-wheat belt moves further north. However, many issues are unresolved. And a 2007 report on how climate change will affect agriculture in the Canadian prairies stated, "The net impacts are not clear and depend heavily on assumptions including the effectiveness of adaptation." This bring us back to the topic of this meeting: adaptation may have tremendous effects in terms of crop yields, agricultural economics and food security.

Modus Operandi

The 2001 US National Assessment provides a convenient example of how we go about studying this. Older global-climate models predict that annual mean temperatures will increase and incrementally so into the future. So one starts with these types of climate changes and then uses them to drive crop models. One study used the EPIC group of models. With the level of CO_2 kept at the baseline condition, in this case 365 parts per million (ppm)—known as the "climate change only effect"—increases in yield were predicted in northern areas and some decreases in the south. However, when the CO_2-fertilization effect was included, in general things became more positive with larger increases in yield.

These yield changes for all major economically important crops are put into agricultural economic models, which was done for the US Assessment. These models are highly complex. Considering the 2030s and 2090s, yield increases were projected for both, with economic benefit. Again, what's the problem? For one thing, if we look at a different model, one from the Canadian Climate Center, which had some larger decreases in precipitation, it projected decreases in economic benefit for the whole of the United States in the 2030s. Clearly, uncertainty in the climate is important.

EXPERIMENTAL APPROACH

The above studies were dependent on crop models driven by climate-change information. The US Climate Change Science Program in 2008 released a report on the impact of climate change on agriculture, water resources, *etc*. Rather than approaching this from a climate-modeling perspective—which has been a dominant method—it looked more at things from an experimental point of view, which is an interesting contrast. In general, compared to the results from the IPCC, the projection was less optimistic, particularly regarding the direct effects of CO_2[2].

These analyses are tending to become more and more current. Fifteen years ago, the focus was on what to expect in the year 2100. Now there's more emphasis on the next 25 years, which is an indication of how much more seriously the problem is being taken. It's no longer an academic exercise. In the 2008 report, they looked at a relatively small temperature change—1.2°C—and a CO_2 increase of up to 440 ppm, *i.e.* conditions that are possible within the next 25 to 50 years. Data from newer experiments, indicated that some of the crop-modeling results may be optimistic about the CO_2-fertilization effects on biomass and yield. For example, with a doubling of CO_2 crop-modeling experiments had predicted a 10% increase, when, in fact, only a 4% increase now appeared to be realistic. So, more uncertainty.

Table 1 provides US results for the effects of a 1.2°C rise in temperature plus CO_2 fertilization from experiments with which they developed statistical relationships. The corn and soybean data are from the upper Midwest. Corn's slightly positive response to increased CO_2 resulted from improved water-use efficiency; however an overall 3% decrease occurred under these conditions due to adverse effects of increased temperature. Soybean was the only crop to respond positively to the increased temperature. Overall, the C4 species, corn and sorghum, were adversely affected; although the C3 species responded positively, things are now not looking as positive.

TABLE 1. EFFECTS OF INCREASES IN TEMPERATURE (OF 1.2°C) AND CO_2 (TO 440 PPM) ON CROP YIELDS (HATFIELD ET AL., 2008)

Crop	Effect of temperature	Effect of CO2	Effect of both
Corn	–4.0	+1.0	–3.0
Soybean	+2.5	+7.4	+9.9
Rice	–12	+6.4	+5.6
Sorghum	–9.4	+1.0	–8.4
Cotton	–5.7	+9.2	+3.5
Wheat	–6.7	+6.8	+0.1

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[2] In general terms, higher atmospheric CO_2 concentrations are expected to increase photosynthetic rate and improve water-use efficiency, thus increasing crop yields.

CO_2 FERTILIZATION

Research on the effects of increased atmospheric CO_2 has been on-going since the early 1980s. Although it was one of the first aspects of greenhouse-gas research to be explored, basic uncertainties remain. In 2006, Stephen Long and colleagues suggested that older enclosure studies had affected the environment more than recent FACE[3] experiments and given overly optimistic indications of the effects of CO_2 fertilization, hence global food security might be more threatened than had been projected. In 2007 several groups looked at this. Francesco Tubiello and colleagues (2007) re-analyzed the data of Long *et al.*, and concluded that the simulated crop responses to elevated CO_2 as implemented in key crop models were consistent with the FACE results. Ziska and Bunce (2007) emphasized the importance of quantifying uncertainties, so that rather than taking results from a curve-fitting we look at the uncertainty around the curve. This debate hasn't been resolved, but it is important with respect to whether or not CO_2-fertilization can offset decreases due to increased temperatures.

EXTREME EVENTS

Extreme events in agriculture is a topic that has received particular emphasis in the past 10 years. For example, the drought in the Canadian prairies in 2001–2002 caused losses in agricultural production equivalent to \$3.6 billion, with Alberta and Saskatchewan particularly affected. Net farm income was negative for several provinces. However—and this occurs in crop-modeling studies as in reality—the adaptation measures could not completely mitigate the drought impact. This demonstrates that, even in advanced western society, increased adaptive capacity will be important.

Another example is the European heat-wave of 2003. I was living in Italy and had never seen so many fields of corn completely desiccated; they lost 36% of their yield. France's 2003 corn crop was 30% lower than in 2002. Wine production was the lowest in 10 years, and economic losses to the EU totaled €13 billion. This is important, because when we talk about adaptation, it is usually over the long term, whereas adapting to these kinds of extreme events is much more challenging.

In the spring of 2008, parts of the Mississippi River were 7 feet above the flood stage, inundating thousands of acres of cropland and resulting in agriculture losses of \$8 billion.

UNCERTAINTY

A few years ago, we looked at a higher resolution climate-change scenario, using a regional climate model vs. the Australian global model. The global model drove the regional model. The higher-resolution scenario was much more draconian: precipitation decreases were greater compared to those predicted by the coarse-resolution model. And we used other regional modeling results for the United States. For soybean, large differences were found; yield decreases were predicted, particularly in the southeast, in both cases, but they are

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[3] Free air CO_2 enhancement.

much more severe with the regional climate modeling. So, scale can make a difference. But, which do we believe? We don't know.

ADAPTATION

An issue that has not been dealt with thoroughly for using crop-modeling studies is the pacing of adaptation. My colleague Bill Easterling, who is part of our southeast study, looked at what happens if you follow different types of curves, assuming that farmers do not all adapt at the same moment. What happens when adaptation occurs gradually as part of a process? The "no-adaptation" case was compared with the "clairvoyant" case in which farmers adapt immediately. Overall, as you would expect, results are somewhere in the middle. Very few studies have shown what adaptation would look like in real time.

My colleague John Riley has studied factors affecting rate of adaptation. It is important to realize that variety development takes 8 to 15 years and variety adoption takes 3 to 14 years These processes have different time scales, therefore pacing of adoption of adaptation is important.

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She has a PhD in geography/climatology from the University of California at Los Angeles. Her published research is mainly in climate-change scenario formation, quantifying uncertainties, and climate-change impacts on agro-ecosystems. She has most recently published papers on the effect of uncertainty in climate-change scenarios on agricultural and economic impacts of climate change, and quantifying uncertainty of regional climate change. She contributed to the Intergovernmental Panel on Climate Change 1995, 2001, and 2007 Assessments regarding climate variability, impacts of climate change on agriculture, regional projections of climate change, climate scenarios, and uncertainty in future projections of climate change. For the 2007 report she was lead author for the chapters on Regional Projections of Climate Change in Working Group 1 and New Assessment Methods in Working Group 2.

Dr. Mearns is a member of the National Research Council Climate Research Committee and of the Human Dimensions of Global Change Committee. She was made a fellow of the American Meteorological Society in January 2006.

Climate Change Overview and Projections

Q&A

Moderator: Graham Scoles
University of Saskatchewan
Saskatoon, Saskatchewan

Steven Pueppke (Michigan State University): All of the discussions spoke, to one degree or another, about climate change and farmers, and I was wondering if anyone has talked to farmers and to gauge their opinions on climate change—whether they believe it is occurring, whether they're prepared to respond to it—issues of that sort. I realize that probably doesn't fall within the direct expertise of any of the speakers, but I'm curious about where the rubber meets the road part of it, which is with the agricultural practitioners.

Raymond Desjardins: I can start answering it. We have a good program. We have developed a greenhouse-gas calculator and the Saskatchewan Soil Association has put a lot of money into training farmers in its use. So, they are interacting with the producers quite a bit in this format. We are at least familiarizing them with the climate-change issue and this calculator allows them to say, "If I do this or that, what will happen to the greenhouse-gas emission on my farm?" After they put in the information for their farms they will know a lot more about climate change and the impact of what they do on greenhouse-gas emissions.

Linda Mearns: In the United States there is a lot of work with stakeholders and in particular there are grants funded by NOAA[1] that are geared towards working with stakeholders. In the one for the southeast, they have worked extensively with farmers, talking to them about adaptation, how they see climate change and what adaptations they envision.

Francis Zwiers: My interaction with the agro-industry community hasn't been with respect to climate change, but earlier in my career I dealt with seasonal forecasting issues. From time to time we held meetings in western Canada to bring people from Environment Canada, who had knowledge of seasonal forecasting, together with producers to learn from producers what types of information they would like to receive from us and

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[1] National Oceanic and Atmospheric Administration.

to understand their concerns. My impression from those meetings was that the kinds of questions that producers had for their own farms were often quite different from the kinds of things that we imagined that we could produce that might be useful to them. Maybe there wasn't an adequate conversation between the two communities. Typically, somebody would get up at a microphone and say that what they would really like to know was the likelihood of a damaging thunderstorm or other extreme weather event during harvest time. Of course we were not in a position to make that kind of forecast 3 months in advance, and we would try to respond and say that we were in the business of trying to forecast average conditions a season in advance and do that on a global scale, and since they were selling into a global market wouldn't it be useful for them to know something in hedging their bets here in this country and wouldn't it be useful for them to know something about growing conditions elsewhere. But the people we were talking to at the time weren't thinking in that particular way, and I think that was largely because we weren't effectively explaining our products and their utility.

Desjardins: One more point—my colleague and I have just published a book, *Better Farming Better Air*. I will put a copy on the desk and anyone interested can get a copy by writing to me. It deals with the impact of climate change on farming practices.

George Khachatourians (University of Saskatchewan): Data were presented that the animal production industry is responsible for 61% of the GHGs in Canada. You listed the species of animals. What would be the contribution of aquaculture should we substitute one with the other?

Desjardins: It was 61% of greenhouse gas emission from agriculture, of which agriculture contributed only 8.5%. So it's 61% of 8.5, or about 5% of the emissions in Canada. Aquaculture: I don't know much about it. I suspect there would be a bit of methane emitted, but I would think it would be quite low. We have counted the greenhouse-gas emissions for practically everything, but we didn't estimate it for fish yet, because you have to count the crop complex that you use to feed the fish; we have done that for poultry, beef and pork, but I suspect that the emission from aquaculture would be low by comparison.

Scoles: Do you have another question?

Khachatourians: The other question is related to adaptation. The adaptation phenomenon follows initiation; people in the next wave follow and then, of course, the system either collapses or continues. My feeling is that another phenomenon is occurring *vis-à-vis* farmers. The current generation is technologically, and even informationally, so knowledgeable that they don't necessarily have to absorb the diffusion of adaptation. They might just simply abandon, and choose other professions and other things. So, we have a dilemma. On one hand we have the most educated, most informed population that should embrace adaptation, yet on the other hand they have "other options." What would your comments be on this one?

Mearns: That's an interesting point and I think it illustrates several things that are beginning to happen in, let's say, the study of impacts and adaptation, and that includes things like migration and change in job category. The younger, more technologically agile farmers may be able to make the best go of farming because they would be among the early adopters; hence, it's not clear to me. It would be interesting to study whether or not it would result in more abandonment of farming or injection of new life into farming.

Tom Wilson (Pennsylvania State University): Dr. Desjardins, you mentioned that carbon sequestration was a reversible process but sensitive to changes in climate and the uncertainties surrounding that. Can you talk a little bit about that and the dynamics?

Desjardins: When you change from intensive tillage to no-till, you will sequester carbon. But if you cultivate the land again, it won't take long to lose the carbon that you sequestered. With the increase in temperature, we expect that there will be more decomposition of the soil organic matter with loss of carbon as carbon dioxide. That's why we say it is reversible.

Wilson: So the loss of organic matter is large enough to shift that balance?

Desjardines: Yes.

Audience member: I want to comment on disseminating information to farmers. We scientists are not trained to disseminate information. I think the experts are being neglected: the agricultural extension agents. Those are the ones who can really talk to the farmers. As students, we are being taught to do research, to find out, not to disseminate information. Extension agents know how to pass information across to farmers.

Mearns: I agree. Interestingly enough, in the area of climate change, at least in the United States, the agriculture extension service is considered a good model for what we would need for climate change in general. In other words, we kind of need an extension service on climate-change information. And something like that may develop in the United States, where we are rapidly gearing up for the development of climate-services programs. It will require working actively with farmers to come up with what information is really useful to them and some scientists are interested in doing that, like those at the University of Florida. On the other hand, some scientists are much more theoretical and not interested in communicating to general stakeholders. It's partially a matter of personal preference, but we need everybody who is interested in communicating to participate.

Desjardins: I might add that, regarding the course I mentioned, the trainees who, in turn, are training farmers to use the calculator have a set of questions they are going to ask the producers and then they will come back to us and hopefully we will be able to improve the calculators so they will be more useful for the farmers.

Mark McLellan (University of Florida): I come from a very interesting state. Florida is a peninsula with a large population and a large agribased business. I have extraordinary confidence in the ability of farmers to adapt. What drives fear into our farmers are catastrophic events. Florida deals with catastrophic events regularly: hurricanes. When we talk about massive rainfall and extraordinary drought, these are things that drive fear right to the core. One of the options is to sell the land, and we worry about harvesting fire hydrants instead of harvesting citrus. It's a real concern. My question is, "Are we moving into a realm of more-dramatic and more-extensive catastrophic climatic events?"

Zwiers: Linda and I were both involved in another one of those US climate-change science plan assessment products on extremes, which can be found on the US global climate-change program website. Look for SAP 3.3. One of the things that this report focuses on is hurricanes, on what we know and don't know about them, and one of the things that I learned in the process was that if you have three people who study hurricanes in the room then you have a hurricane. We understand some aspects of what controls the development of these storms and the conditions under which they will form, but we don't have complete process understanding. It's not a phenomenon that is represented directly in global climate models; you have go to the high end of regional climate model resolutions—at the 15-, 10- or 5-km scale—in order to simulate these things well. Depending upon how you look at the data and what data you look at, you might convince yourself that there has been a large change in the frequency or intensity of hurricanes in the North Atlantic, or you might convince yourself that the frequency is not all that large and the change in intensity is not all that large. Depending upon who looks at this, you might come to the conclusion that future storms are going to be much more intense than at present or moderately more intense than at present. We are not able to give a clear picture. And the observational evidence from one basin in which tropical cyclones are found is not so consistent with the data from other basins in which tropical cyclones are found. We are still in the process of trying to understand why that is the case and we are understanding for example that hurricane formation in the North Atlantic has a lot to do with large-scale global variations and circulation, such as the state of the North Atlantic oscillation. So, lots of things make this particular picture hazy. There will be another opportunity for the global community to make an assessment on extremes, and I think we will come closer to your particular question, which has to do with whether climate change is causing more frequent disasters and is it affecting our ability to manage those disasters and are we managing disasters effectively at the moment. The IPCC recently made a decision to produce a special report on extremes and managing the effects of extremes. We just had a scoping meeting on that and it will deal with what we understand about how extremes have been changing in the physical climate system and how they will continue to change in the future.

Mearns: Francis addressed one of the more complex extremes. There are other extremes that could have catastrophic effects that we are more certain about, for example, heat waves, however you want to define them. We know that very high heat in certain phenological stages in crops can be disastrous. In 1983 in the US corn belt, there was tremendous loss in yield not because of drought but just because of a series of days above 95°F around fertilization. Those are absolutely inevitable, I would say. The other is, of course, more extreme precipitation, so more flooding devastation is possible, like we had in spring on the Mississippi River. Also, clearly, is the problem of heavy precipitation causing soil erosion. A lot of thought is being given to weather extremes and more attention will be placed on it such as through IPCC special reports.

Myles Frosst (Agricultural Institute of Canada): My question has to do with adaptation and communication—the reference to farmers being aware of this sort of analysis and what steps they can take. My sense is that, in the schools of agriculture and bioresources, or by whatever name, *some* percentage of undergraduates are being exposed to IPCC-type analysis such as the work coming out of Agriculture and Agrifood Canada on climate change and adaptation. So my first question is, "What percentage of undergraduates at schools of agriculture are being brought up understanding this ethic and this certain information?" And the second is, "How do you personally rely on your views getting across to non-ag, non-environmental senior public servants and their bosses, so that when decisions are made around cabinet tables as to regulatory matters, funding, *etc.*, they can make informed choices?"

Desjardins: I'll try to answer the second question.

Mearns: Can't you answer the first?

Desjardins: I can't. I'm not a teacher.

Zwiers: I can't.

Mearns: We can't answer the first question. None of us.

Desjardins: In response to the second questions, we work closely with policymakers. We prepare treasury-board submission. Like in Ag-Agfood Canada, I am fortunate that policymakers interact with our research group and we get our message to the policymakers about our needs in research. And we have been team-working on preparing treasury-board submissions, so this works quite well as far as I'm concerned, in some departments. In other departments it doesn't work quite as well.

Scoles: For question one, we have about ten graduate students in the room. How many of them are aware of IPCC? All of you.

Joanne Puetz Anderson (South Dakota State University): At South Dakota State University, a lot of ag students take meteorology and we deal with the feedback cycles—the carbon cycle and the water cycle, and we talk about climate change. We never say global warming, but we do say climate change.

Zwiers: If I can respond to the second question, I have a complicated answer and in three parts. I work two levels down from the assistant deputy ministry, and so we think a lot about how to feed our stuff up to policy people. I am part of the Atmospheric Science and Technology Directive of Environment Canada, and we have an air-quality group, a climate group, and a meteorological research group. The air-quality group has good interaction with policymakers because they are involved in science that is directed at regulation; the policymakers understand what they are doing. They are making rules on the kinds and quantities of materials that can be emitted into an airshed and what standards are appropriate for Canadian health, Canadian air quality, and so on; this is a direct working relationship between the policy types and the scientists. On the climate side, our science has largely been aimed at contributing to the IPCC process, so we have been studying global climate issues, and until recently have not been focused on regional aspects. Therefore, the pathway used for informing the policy committee has been mainly by contributing to the IPCC process and making sure that the IPCC report is a respected document for government use as a basis for negotiations internationally. We sometimes have to pass information up to our negotiators, but in Canada the negotiators tend to hold their cards close to their chests and we scientists find it hard to know what information they need. That communication doesn't work as effectively, so we use the indirect IPCC route.

Abraham Blum (Plantstress.com): Farmer adaptation is outside the context of catastrophes. Farmers cannot adapt to crop-killing drought or crop-killing heat or flood. There is no way to adapt to those. A scientist at the International Rice Research Institute who has worked with farmers coping with drought in southeast Asia for 10 years reported that one of the ways a farmer in India copes with drought is to sell a child into forced labor. We don't consider this adaptation. We cannot deal with catastrophes. My second comment is more technical. Dr. Mearns stated that increased CO_2 concentration in the atmosphere increases water-use efficiency and, therefore, increases yield. However, water-use sufficiency does not equate with higher yield. In rain-fed cropping systems, higher water-use efficiency is often achieved by reduced water use and not by increased yield. It's a ratio, of which you have to consider both sides.

Scoles: Any comment? No?

Desjardins: I will just say that better-managed crops use water more efficiently.

Tajinder Grewal (Saskatchewan Research Council): It's nice to hear that with global warming we will have new crops and more yield. What new crops are you expecting in the next 30 to50 years, and what crops will not be grown after 30 to 50 years?

Mearns: That's a very big question.

Scoles: Anybody want to take that on?

Desjardins: One of the things that I mentioned is that a highly reflective crop might help a little bit because it will increase the albedo. There have been several papers recently on that. There is talk about a C4 variety of rice which would be a major breakthrough, another Green Revolution. Any crop that avoids having to use nitrogen—a nitrogen-fixing crop would be a major breakthrough because whenever you apply nitrogen you produce 1 kg of carbon per kg of nitrogen fertilizer produced. That would be a major improvement.

Kelly Pitman (Texas A&M University): Dr. Mearns you mentioned that you use regional climate models in your research. I'm doing research on climate change effects on crops in South Texas, and we also have a lot of extreme events. For example, we are now in an exceptional drought, and last summer hurricanes flooded our fields. Can you suggest tools that I can use for crop modeling in our region? I'm having trouble finding something that I'm satisfied with.

Mearns: Do you mean climate-change scenarios that you could use?

Pitman: Well, more like a software program to assess climate change in my region.

Mearns: The slides that I had to skip would show that we can meet all your needs practically immediately. At the North American Regional Climate Change Assessment Program, we are using six regional climate models at a 50-km resolution and four different global models. Therefore, my first advice to you would be to look at our website. A users meeting will be convened in early September. Google "NARCCAP."

Claire Sullivan (University of Saskatchewan): Dr. Desjardins, you talked about how we can adapt human behavior to affect climate change including change in diet. You suggested eating less, consuming less meat, and I am curious about the difference between us consuming less meat or producing meat more sustainably. In a previous NABC report, they spoke about using animal by-products as part of a biobased industry.

Desjardins: I think that consumers will probably want more meat in the future, so we'd better look for alternative production methods. I mentioned, for example, a farm where they have an adjacent ethanol plant. They feed cattle with byproducts from the ethanol-production process, using corn as the feedstock. The animals produce manure that is transferred to biodigestor from which energy is produced. We might come to this type of farming system if we want to retain our lifestyle. Otherwise, we are faced with choices. For example, I read recently in the *New Scientist* where you eat some meat but in reduced amounts, and that can help considerably. Soy protein is an alternative, but I don't think we will change consumers' desire for meat. Meat may be produced from forages that have few other uses, and forage crops are excellent for sequestering carbon. We need to look at all options.

Module 2: Genetic Approaches to Crop Adaptation

Functional Genomics and Abiotic-Stress Tolerance in Cereals

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Environmental or abiotic stresses such as high temperature, low water availability, salinity and mineral toxicity and deficiency frequently affect plants in agricultural systems, and represent major limitations to the yield and quality of barley (*Hordeum vulgare* L.) and wheat (*Triticum aestivum* L. and *turgidum* L.) crops. It is common for many abiotic stresses to challenge a crop simultaneously. For example, the occurrence of high temperatures is common during periods of limited water availability, and often under these conditions plant roots encounter high concentrations of salt and boron in the subsoil.

Grain yields in Australia are vulnerable to climatic variation. This is evident from wheat yields over the past decade, which have ranged from approximately 1.1 to 2.1 t/ha. In 1982, 1994 and 2002, major droughts (high temperatures, low rainfall) across southern Australia had drastic effects on cereal production, with less that 10 million tonnes of wheat produced in these years. This is in contrast to favorable years, such as the 1983/84 season following the 1982 drought, which produced a wheat crop of 22 million tonnes. In recent years, the area planted to cereal crops in Australia has increased, largely as growers switched from sheep farming due to decreasing wool prices. Average wheat yield per hectare has also been rising, at a rate of approximately 1.6% per year over the past 20 years.

Historically, improvement of tolerance to abiotic stresses has been a major target of plant-breeding programs globally. The major challenge, however, results from the complex nature of abiotic-stress-tolerance traits and the difficulty in dissecting them into manageable genetic components amenable to molecular breeding. In crop breeding, advances in molecular biology and genomics have had a large impact on the speed of identification and characterization of genes and genetic regions associated with quantitative and qualitative traits. Marker-assisted selection through the use of high-throughput marker systems is currently being used extensively in breeding programs to improve selection efficiency, accuracy and to direct focus towards traits of importance. As key genes are identified, efficiency increases and opportunities for genetic engineering are realized. An underlying factor important for gene discovery in relation to traits of interest is naturally occurring genetic diversity. This is a fundamental aspect of research into abiotic-stress tolerance, and discoveries of abiotic-stress-tolerance genes in cereals is revealing novel mechanisms of adaptation in crop plants and their wild relatives. Genetic-diversity screening is a starting point for many functional genomics projects relating to gene discovery. The extensive genetic diversity available within the grasses makes this an excellent system in which to work on abiotic-stress tolerance.

CASE STUDIES: ABIOTIC STRESSES OF IMPORTANCE TO THE SOUTHERN AUSTRALIAN CROPPING SYSTEM

Boron Toxicity

Boron is one of the eight elements that are essential for healthy plant growth. Its deficiency in crops is well known, and has been intensively studied. However, in semi-arid areas of the world such as Southern Australia, West Asia and North Africa, boron content in soils is high and can limit productivity. In South Australia, more than 30% of soils in grain-growing areas have levels of boron considered toxic to plant growth. Yield penalties of up to 17% between adjacent areas of barley have been attributed to differences in shoot-boron concentration, and similar figures have been reported for wheat (Cartwright *et al.*, 1984; Moody *et al.*, 1993). The primary mechanism of tolerance appears to be similar for all species studied: an ability to maintain low concentrations of boron in plant tissues (Fig. 1). Identification of the genes controlling this important trait have been a major focus of our work at the Australian Centre for Plant Functional Genomics (ACPFG).

Previous work at the University of Adelaide over more than two decades has resulted in the identification of the major genes involved in boron-toxicity tolerance in barley (Jefferies *et al.*, 1999; Sutton *et al.*, 2007) and wheat (Paull *et al.*, 1995; Jefferies *et al.*, 2000). The progression of this work follows a pathway that in many ways parallels technological development in areas of modern plant science, from traditional genetic studies determining the underlying genetic basis for tolerance, mapping studies to determine more accurately the chromosomal position of loci involved (also known as QTL, quantitative trait loci), physiological approaches to investigate the mechanisms at play, to the more-recent fields of functional genomics to identify candidate genes and clarify their roles. We recently identified the gene *Bot1* in barley, underlying the most significant QTL associated with boron-toxicity tolerance in this species. The locus has been the target of breeding programs for more than 15 years in Southern Australia, using marker-assisted selection. The jury is still out as to the success of this conventional introgression approach, as lines carrying the introgression can potentially be lower-yielding than the recipient cultivars. It is unknown if this is due to pleiotropic effects of the tolerance gene itself, or due to unwanted deleterious alleles from the otherwise unadapted, but boron-tolerant, donor landrace.

Identification of the gene involved now places us in an exciting position. Not only do we understand the molecular basis for tolerance, but we can now also provide breeding programs with lines carrying recombination events close to the tolerance gene, helping to break unwanted associations. We can also focus on the generation of boron-tolerant germplasm using genetic transformation. This work represented the first isolation of an abiotic stress QT locus in a cereal, and revealed novel concepts on gene duplication and evolution of tolerance to abiotic stress in cereals.

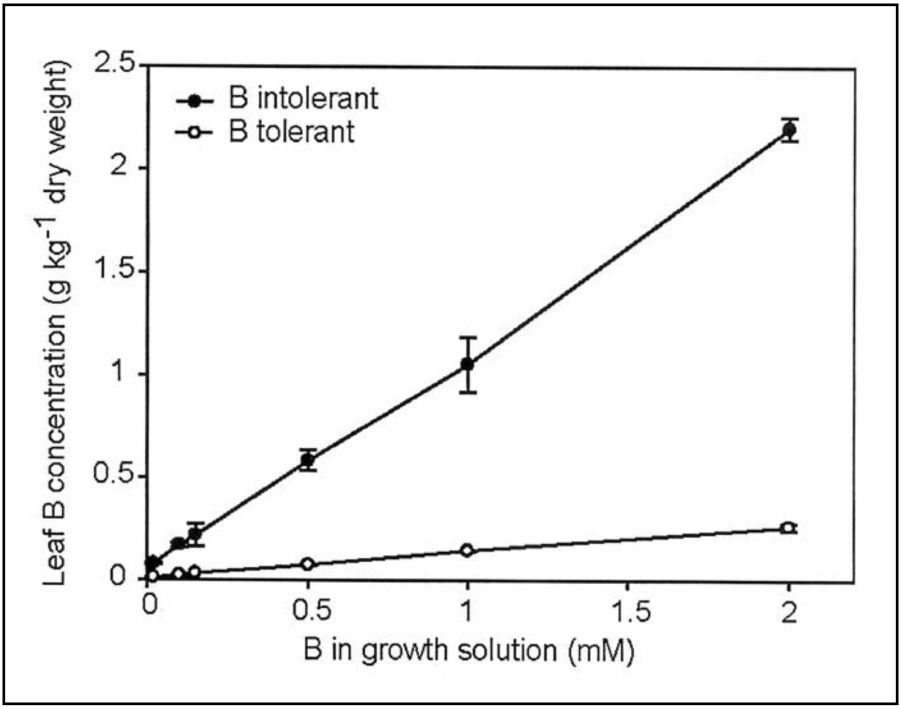

Figure 1. Genetic variation for boron tolerance in barley.

Salinity

Salinity is a major abiotic stress affecting crops in Australia and throughout the world. More than 800 million hectares of land are salt affected globally, accounting for more than 6% of the total land area (Munns and Tester, 2008). In Australia, some 20,000 farms may be affected by salinity: of 1,969,000 hectares of arable land affected by salinity, 820,000 may be unusable (ABS, 2002). Western Australia, the largest wheat- and barley-producing state in Australia, is the worst affected with yields on 51% of the state's farms constrained to some extent by saline soils. In most crop plants, the main toxic component of salinity is the sodium ion (Na^+), which interferes with metabolic processes such as enzyme activity and protein synthesis, as well as causing osmotic stress through the reduced ability of cells to obtain and retain water. Due to these toxic effects, crops grown on saline soils have significantly reduced yields.

Plants use three main mechanisms with which to tolerate salinity stress (Munns and Tester, 2008):

- osmotic-stress tolerance, the ability to maintain growth under osmotic stress, a process that causes stomatal closure and reduced cell expansion in root tips and leaves,

- Na^+ exclusion, the reduction of Na^+ accumulation in shoots by Na^+ exclusion in the roots, and
- tolerance of tissues to accumulated Na^+ and possibly Cl^-, requiring, in most cases, compartmentation of Na^+ and Cl^- at the cellular and intracellular levels.

The focus of salinity research at ACPFG is diverse and covers aspects within these three areas. Functional genomics provides new opportunities to understand these processes in the plant, enabling the identification of genes involved and providing opportunities to generate plants that are able to survive and produce viable yields on saline soils.

Drought

Drought tolerance is a key trait of interest for cereal breeding. Predictions of human-population growth globally, and accompanying shortages of arable land and water supply emphasize a need for crop-plant development in this area. In Australia, drought stress continues to be a major factor affecting the productivity of our rain-fed cereal crops. Since 2001/02, much of Australia's most productive agricultural land, primarily in the southeast, has experienced conditions of higher-than-average temperatures and lower-than-average rainfall (ABARE, 2009). In 2007, after several preceding years of drought, we witnessed one of the hottest growing seasons on record across much of Southern Australia, with crop losses much larger than expected. This trend of declining rainfall and increasing temperatures is predicted to continue, emphasizing a need for scientific approaches to develop germplasm adapted to these hostile conditions.

Drought tolerance is a difficult trait to define as it encompasses a wide range of characteristics involving multiple genetic, physiological, cellular and biochemical strategies in the plant. Dissecting drought tolerance to the level of a single gene or group of genes amenable to genetic engineering will be difficult. A major challenge in the use of functional genomics to enhance the development of drought tolerance is to define the system and focus on key traits of interest. ACPFG has been tackling the drought problem using three strategies. The first is a forward genetic approach aimed at defining the genetic basis for differences in tolerance in adapted germplasm. The second aims to build a database of transcript, protein and metabolite responses of wheat and barley exposed to drought stress that can be used to support candidate-gene discovery. The third involves specific targeting of genes with known roles in drought-stress tolerance in other species, such as transcription factors and protein kinases.

One of our core activities involves the genetic analysis of crosses involving elite bread-wheat germplasm that display variation for grain yield under drought-stress conditions in Southern Australia. Figure 2 shows three advanced wheat lines, 'Kukri,' 'Excalibur' and 'RAC875,' from which we have established two large mapping populations. In both cases, 'Kukri' is the drought-sensitive parent, with 'RAC875' and 'Excalibur' representing two different mechanisms for drought response. The populations have now been characterized for more than forty phenotypic traits related to drought tolerance (Table 1) in twenty environments. The key objective of this work is the identification of QTL that influence a range of drought-related traits and ultimately yield under local conditions. The work has identified the location of chromosomal segments associated with the maintenance of yield or yield components under drought-stress conditions. These regions are being targeted in other projects aiming at validation and ultimately the positional cloning of the genes involved.

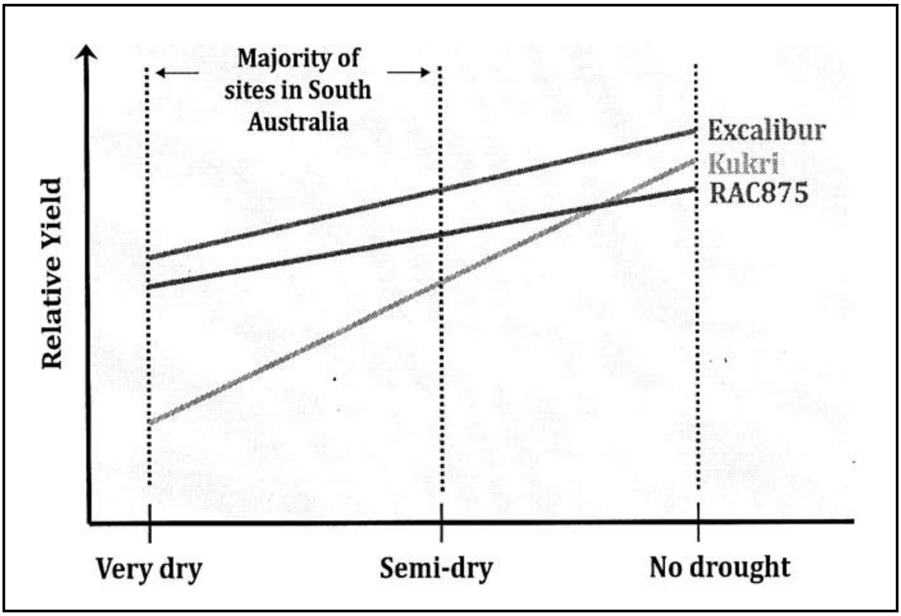

Figure 2. Genetic variation for drought tolerance in wheat
(source: Steve Jefferies, Australian Grain Technologies).

Pipelines for Functional Analysis of Candidate Genes

A crucial part of the pipeline for gene discovery, characterization and downstream delivery of abiotic-stress-tolerant germplasm is the functional testing of candidate genes *in planta*. We have established a cereal-transformation facility that, in 2008, transformed wheat and barley with more than 100 constructs, generating in excess of 1,500 independent transgenic events. Of importance and key to our strategy is the ability to reliably and routinely transform elite breeding varieties of wheat and barley with genes relevant to key traits, such as drought tolerance. This provides a significant advantage in the testing of candidate genes, by allowing analysis of gene effects in otherwise highly adapted backgrounds. A significant contribution to the downstream analysis of material generated from our gene-discovery programs is the establishment of the Australian Plant Phenomics Facility (www.plantphenomics.org.au), directed by Professor Mark Tester (ACPFG, University of Adelaide). The facility, due for completion in December 2009, will provide a state-of-the-art plant-growth complex, comprising 2,400 m^2 of glasshouse and 250 m^2 of growth-room space, allowing the analysis of more than 100,000 plants annually. The facil-

Table 1. A selection of drought-tolerance traits measured in wheat drought-mapping populations (source: James Edwards, ACPFG).

Development	Seed	Leaf	Root
Zadoks (maturity score)	Aborted florets	Leaf rolling	Crown rot
Degree days to heading	Fertile seeds/spike	Glaucousness (waxiness)	*Rhizoctonia*
Days to heading	Spikes/m^2	Canopy temperature	
Days to anthesis	Grains/m^2	NDVI (canopy reflectance)	
Days to senescence	1,000-grain weight	Water-soluble carbohydrates–content	
Early vigor	Screenings (<2 mm)	Water-soluble carbohydrates–per unit area (m^2)	
Plant height	Hectare litre weight	Water-soluble carbohydrates–per tiller at jointing	
Head length	Yield (kg/ha)	Water-soluble carbohydrates–per tiller at maturity	
Peduncle length		Tipping	
Number of plants at jointing		Flag-leaf length	
Number of tillerss at jointing		Flag-leaf length	
Tillers/plants at jointing		SPAD chlorophyll-meter reading	
Number of tillers at maturity		Anthesis biomass	
Tillers/plant at maturity		Harvest index	
Aborted tillers		Maturity biomass	
Aborted tillers/plant			
Grain-filling duration			

ity will be based around automated image analysis; plants will be grown under controlled conditions and delivered to high-resolution imaging stations by a network of 1.2 km of conveyor belts. Accurate and detailed measurements of the phenotypic characteristics of germplasm collections, breeding populations, mutant populations and transgenic material will be possible. Non-destructive measurements will be possible of:

- shoot mass, leaf number, shape, angle, leaf color and senescence using visible-spectrum images,
- leaf water and carbohydrate content using near-infrared images,
- and leaf temperature using far-infrared images.

The Australian Plant Phenomics Facility will relieve a significant bottleneck in the area of plant phenotyping, limiting capability to capitalize on substantial investments in functional genomics and molecular breeding technologies in Australia.

CONCLUSION

Traditional molecular genetic studies have contributed greatly to our understanding of the underlying biology of tolerance to abiotic stresses. We know a great deal about the genetic control of traits for tolerance to major abiotic stress in cereal crops, such a boron tolerance, salinity tolerance, reproductive frost tolerance, and aspects of drought tolerance. This information has proven especially useful in breeding programs able to exploit molecular methods to aid selection. In some cases, the genes involved have been identified and their study is providing fascinating insight into adaptive-evolution mechanisms in plants. Gene identification also provides the opportunity to generate new varieties in the future via genetic transformation with superior abiotic-stress tolerance. Although genetically engineered wheat and barley are not yet grown on a commercial scale in Australia or other parts of the world, it may occur in the future. Functional genomics has a central role in this process, as part of a strategy to provide molecular solutions to pre-existing abiotic stresses, and also to address the prospective changes in our environment.

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SINCE 2003, Tim Sutton has been a research fellow and group leader at the Australian Centre for Plant Functional Genomics, a Commonwealth-funded entity focusing on the application of genomics to address drought, salinity and associated abiotic stresses that severely limit agricultural production in semi-arid environments.

The focus of Dr. Sutton's research is to understand the genetic and molecular mechanisms that enable some plants to survive under sub-optimal soil conditions, such as mineral toxicity and deficiency, and to develop cereals with increased tolerance to these stresses. The work involves collaboration within Australia and internationally, has attracted the attention of the popular press, and has been published internationally, including in the journal *Science* describing the first example of the cloning of an abiotic-stress-tolerance quantitative trait locus from a large-genome cereal. He has presented invited seminars in the United States, Europe and Egypt, and is regularly invited to peer review research papers for journals including the *Plant Journal*, *Genome*, and *Theoretical and Applied Genetics*.

In addition to supervision of graduate students in the area of cereal molecular biology, he is active in community and outreach activities within the Australian biotechnology education sector. He has a PhD in plant molecular genetics from the University of Adelaide (2002).

Enhancing Crop Productivity Through Increased Abiotic-Stress Tolerance and Biomass Production

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Crop yields are limited by a combination of biotic stresses, abiotic stresses, and nutritional factors. Various analyses have suggested that abiotic stress—due primarily to drought, heat, cold or salinity—is the major factor that prevents crops from realizing their full yield potential (*e.g.* Boyer, 1982; Edmeades, 2008). Increases in crop yields through conventional plant breeding result from genetic enrichment by introducing multiple quantitative trait loci (QTLs), including, presumably, QTLs for abiotic and biotic stress resistance. For example, Tollenaar and Wu (1999) have provided evidence that yield increases in corn (*Zea mays* L.) in recent decades have been partly due to enhanced stress tolerance during the grain filling and late-maturation stages.

Separately, recent interest in renewable fuels has led to a substantial increase in ethanol production from plant material. Although the initial emphasis has been on using starch from corn, and to a lesser extent from other food grains, this is unlikely to be sustainable in the long term; alternatives such as cellulose from specially grown "biomass" crops are likely to be a more important substrate for ethanol production. The challenge here is to increase total vegetative biomass rather than seed yield, similar to the approach one might take in forage or silage-crop improvement.

This paper describers several examples of how modern crop technologies, in particular transgenic approaches, may be applied to broaden crop tolerance of various abiotic stresses and to increase total biomass in non-seed crops.

Drought Tolerance

Drought limits crop yields in many parts of the world, and research has identified many genes that may contribute to enhancing plant performance under drought stress. In a recent study, seven independent genes previously shown to confer some tolerance of drought were compared in a transgenic rice study (Xiao *et al.*, 2008). The genes included transcription factors (*e.g. CBF3*), genes involved in abscisic acid (ABA) biosynthesis (*e.g. NCED2*, *LOS5*) and genes involved in oxygen-radical detoxification (*e.g. SOS2*). Many of the transgenic plants carrying these genes yielded more than the wild-type rice under drought conditions. The authors emphasized the importance of evaluating transgenics under both stressed and non-stressed conditions in the field to obtain a full understanding of gene performance.

In a separate study, over-expression of the transcription factor Nuclear Factor Y B subunit conferred protection against drought in *Arabidopsis thaliana* (L.) Heynh. and corn (Nelson *et al.*, 2007). Drought tolerance has also been conferred by expression of a gene for isopentenyl transferase involved in cytokinin biosynthesis (Rivero *et al.*, 2007).

At Performance Plants, research on drought stress has been focused on a key step in the ABA-signaling pathway. It was initially observed that a knock-out of the farnesyl transferase β subunit (FTB) protected *Arabidopsis* plants against drought; however, the knock-out plants exhibited some deleterious effects that delayed flowering and reduced yield (Pei *et al.*, 1998). Subsequently it was shown that down-regulation of FTB in *Arabidopsis*, using either anti-sense or RNA interference, resulted in a drought-tolerant phenotype without the negative effects of the full knock-out (Wang *et al.*, 2005). The primary physiological mechanism underlying this response is enhanced sensitivity to the ABA signal produced under drought-stress conditions, resulting in more-rapid stomatal closure, increased water retention in the plant, and increased seed yield (Figure 1).

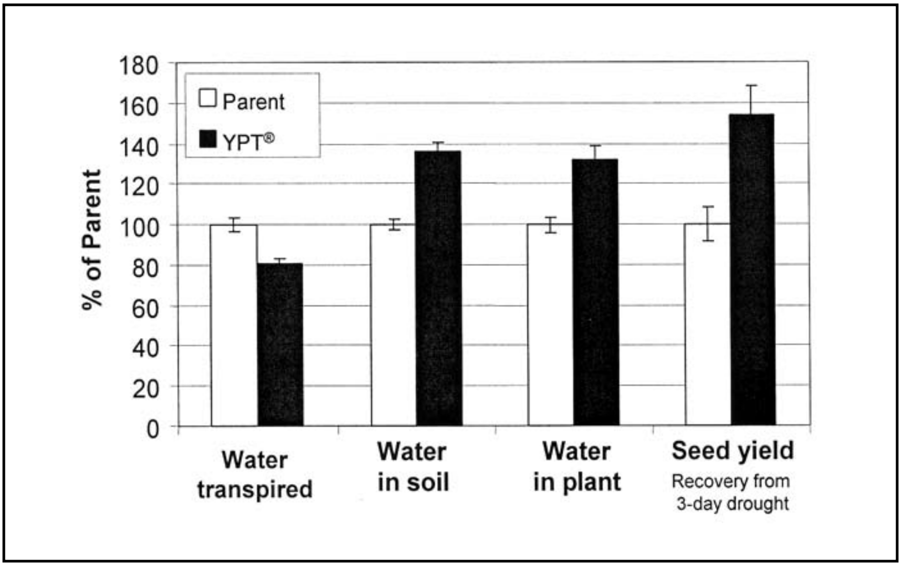

Figure 1. Leaf transpiration, soil-water content, plant-water content and seed yield in *Arabidopsis*, conferred by down-regulation of farnesyl transferase β (YPT®). Data are expressed as percent of the parent (wild-type) control (Pei *et al.*, 1998).

This research was subsequently extended to the farnesyl transferase α subunit (FTA; the functional farnesyl transferase protein is a heterodimer of the α and β subunits, both of which are required for enzyme activity). Down-regulation of FTA also resulted in a drought-tolerant phenotype in *Arabidopsis* (Wang *et al.*, 2009).

Down-regulation of FTB or FTA in canola (*Brassica napus* L.) has been shown to confer protection to plants growing in the field over several growing seasons in western Canada (Wang *et al.*, 2005; Wang *et al.*, 2009). Under well-watered conditions there was no yield drag and all agronomic and seed-quality parameters were similar in the transgenic and wild-type plants. In one field experiment, the yield of wild-type canola was significantly reduced under limited irrigation conditions, whereas the yield of two independent transgenic lines with down-regulated FTB activity was not affected under these conditions (Figure 2). Overall, yield increases of up to 26% over the wild-type have been observed in transgenic canola growing under dryland conditions in western Canada.

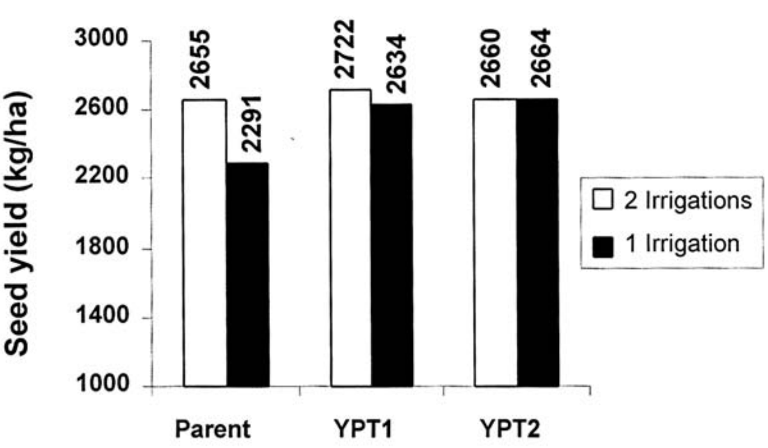

Figure 2. Seed yield of parent (wild-type) canola and two independent FTB down-regulation lines (YPT1 and YPT2) grown under well-watered and reduced-irrigation conditions. Irrigation was applied twice (=well-watered) or only once during the flowering period. The yield of the FTB down-regulation lines under one irrigation was significantly higher than that of the parent under similar conditions (Wang *et al.*, 2005).

The ABA-signaling pathway resulting in stomatal closure is highly conserved in higher plants. This approach of down-regulating FTA/FTB is currently being extended to several other important crops, with the aim of protecting their yields under water-limiting conditions.

HEAT TOLERANCE

Recent concerns about global warming have stimulated interest in the effects of high temperatures on crop production and crop yields. In light of the anticipated temperature increases, acquisition of thermotolerance is seen as a key strategic target in maintaining crop yields (Wahid *et al.*, 2007). Various analyses (*e.g.* Battisti and Naylor, 2009; Lobell and Asner, 2003) suggest that increasing temperatures will pose a major constraint to crop production in the future. A recent study suggested that the warmest summers observed in the tropics and subtropics in the past century may be seen as normal by the end of the 21st century (Battisti and Naylor, 2009).

Existing data already illustrate quite clearly that high temperatures frequently limit crop-seed yields. Field-grown canola yields were significantly reduced by temperatures of ≥30°C during flowering. The yield of three *Brassica* species, *B. napus*, *B. rapa* and *B. juncea*, were all reduced by high-temperature stress, although reductions were less in *B. rapa* and *B. juncea* than in *B. napus* (Angadi *et al.*, 2000). Recent observations in the prairie provinces of Canada suggest that canola yields are lower in summers in which high temperatures occur during flowering.

A recent retrospective analysis of rice yields at the International Rice Research Institute in the Philippines indicated that increasing temperature was correlated with a reduction in rice yield. The reduced rice yields were correlated with higher night temperatures but not with daytime temperature increases, which were only about one third as high as the increase in night temperature maxima (Peng *et al.*, 2004). Each increase of 1°C in the night-time maximum temperature was associated with a 10% decrease in rice yield. This study highlights the importance of studying the independent effects of increases in day and night temperatures to understand the underlying physiological basis for high-temperature effects on crop growth and yield.

At Performance Plants we have undertaken a large-scale screening program to identify candidate genes associated with heat tolerance. Several have been identified and confirmed as conferring heat tolerance in *Arabidopsis*. Some of these same genes, or their *Brassica* homologs, linked to an appropriate promoter, confer heat tolerance in flowering canola plants (Figure 3). A selection of these putative heat-tolerant lines will be field-tested for the first time in 2009.

OTHER ABIOTIC STRESS-TOLERANCE TRAITS

Although not reviewed in this paper, cold and freezing tolerance has received as much attention as drought over the years. Substantial improvements have been made in low-temperature tolerance through conventional breeding, more recently enhanced by the use of molecular markers associated with the trait. Although many genes have been identified as putative cold-tolerance genes, it would appear that none of these has yet demonstrated sufficient protection to merit commercialization in large-scale crop production. However, despite the trends of higher temperatures in many regions, protection against the devastating effects of low temperatures, particularly during the sensitive phases of seedling growth and crop maturation, remains an important focus area for crop improvement.

Figure 3. Canola (*Brassica napus*) plants subjected to heat stress during flowering. Left, plant containing transgene for heat tolerance; right, wild-type. (Photo courtesy of Performance Plants Inc.)

Water-use efficiency (WUE) has some elements in common with drought tolerance, in that it can be seen as a mechanism whereby a plant can avoid drought by depleting soil moisture more slowly. However, the physiological mechanisms of the two traits are likely different, as is their place in agricultural cropping systems. WUE is being recognized as a critically important trait in areas where crop production relies on dwindling supplies of sub-surface irrigation water or where there is competition for water between urban and agricultural demands.

Approaches to enhancing WUE center on altering the ratio of CO_2 assimilated per unit of water transpired (Chaerle *et al.*, 2005). In one study, an *Arabidopsis* transcription factor, *HRD*, was shown to increase WUE in rice (Karaba *et al.*, 2007). The transgenic plants in this study exhibited higher shoot biomass under well irrigated conditions and more root biomass under drought stress. WUE was also linked to changes in leaf morphology and mesophyll-cell structure that contributed to higher rates of photosynthesis. It is very likely that we will see considerably more effort in this area of research in the coming years as concerns over water availability increase.

Stress Combinations

Abiotic stresses often occur in combination. For example, heat and drought stress frequently occur simultaneously. Mittler (2006) has emphasized the importance of studying plant responses to combinations of stresses rather than stresses in isolation, since a plant's response and coping mechanism may differ according to which stresses or combination of stresses it is experiencing.

Some stress-protection mechanisms appear to confer tolerance of multiple stresses, for example through effects on energy balance or detoxification of reactive oxygen species generated upon exposure to stress. Down-regulation of poly(ADP-ribose) polymerase (PARP) in *Arabidopsis* and canola increased tolerance of heat, drought and high light (De Block *et al.*, 2004). While this was originally believed to be due to reduced NAD^+ depletion and reduced ATP consumption, subsequent research indicated that reducing PARP expression also induced ABA production, which, in turn, led to induction of a wider range of stress-tolerance genes (Vanderauwera *et al.*, 2007; Metzlaff, this volume[1]). This may provide a common mechanism of tolerance of multiple stresses. In a similar vein, different stresses that result in oxygen-radical production (*e.g.* ozone, high temperature) may be mitigated by common mechanisms that detoxify these radicals.

Clearly, stress tolerance is complex and no single approach can provide a solution to the multiple environmental stresses that a plant might experience during its lifecycle. Further evaluation of novel germplasm and putative stress-related genes under field conditions will be required to develop a robust set of new germplasm better adapted to withstand the stresses a plant may be exposed to.

Enhanced Biomass Production

As mentioned above, there is increasing interest in production of plant biomass for cellulosic ethanol production. A wide range of plant species, monocots and dicots, annuals and perennials, and herbaceous and woody plants, is currently being evaluated for total biomass production. For the business of ethanol production from biomass to be viable, a certain minimum productivity per unit land area will be required to keep substrate costs low.

In addition to selecting and breeding for high biomass-yielding varieties, some effort is now going into the use of transgenic approaches to increase total plant biomass. At Performance Plants we have identified a novel allele of a gene involved in the transition from vegetative growth to flowering. The effect of this allele is to delay flowering, thereby extending the period of vegetative growth. Plants carrying this trait have greater total biomass, larger leaves and thicker stems. Although flowering is delayed, the plants do eventually produce viable seed. This trait is now being incorporated into potential biomass crops for more extensive evaluation under field conditions.

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[1] Pages 73–77.

CONCLUSIONS

Crop production faces many challenges, due to changing environmental conditions and evolving needs for new plant-derived materials. No one approach will provide all the solutions. Rather, progress will be made by combining the existing approaches of breeding, enhanced by molecular markers linked to traits of interest, mining of novel alleles from germplasm collections, and introduction of novel alleles or variants of existing alleles from mutant populations. The path forward will require us to combine all possible approaches to maximize the chance of success in this important endeavor.

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MALCOLM DEVINE joined Performance Plants, Inc., in September 2006 as vice president for crop development and commercialization, bringing extensive experience in both public- and private-sector R&D in agriculture and plant biotechnology.

Dr. Devine obtained his training at the Universities of Glasgow (Scotland), Guelph, and Alberta. From 1987 to 1998 he held a faculty position in the Department of Plant Sciences at the University of Saskatchewan, serving as department head, 1994–1998. He then joined AgrEvo Canada (later to become Aventis CropScience Canada) as head of biotechnology research and spent 3 years in Ghent, Belgium, as head of technology acquisition and licensing for the BioScience division of Aventis CropScience, and later Bayer CropScience, with responsibility for technology evaluation, licensing and collaborations in support of BioScience research.

On his return to Canada in 2004, he spent 2 years as research director at the National Research Council Plant Biotechnology Institute in Saskatoon.

Adapting Crops to Climate Change

Michael Metzlaff
Bayer BioScience NV
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Why do we expend a lot of effort in improving plant responses to sub-optimal environmental conditions? I don't have to go into detail on the growing world population, the need for alternative energy from biofeedstocks, or climate change. At Bayer BioScience, I am responsible for linking our efforts with academic research worldwide. We at Bayer recognize that we have to cooperate with academia to be successful in business because public-sector scientists often cover the early stages in the pipeline of crop development by breeding, including discovery and technology testing of various traits of interest.

Only about 3% of the Earth's surface area is arable land. The breeder's task is to increase productivity of this small area. The other limiting factor is water. Some 70% of global freshwater is used by agriculture. If we can use less water for irrigation and maintain crop yields, we would save resources and enormous amounts of money worldwide.

Our major objective is to close the gap between theoretically attainable crop yields and their actual yields. Abiotic stresses, which reduce attainable yields, can be grouped in terms of genes that are expressed under various stressed conditions, for example heat and drought form a group as do cold, drought and salinity. Drought, which occurs in both groups, has a major effect on plant growth, therefore we need to either adapt or acclimate our crops to resist these stresses.

Energy a Key Factor

When we first considered how to breed plants with tolerance of various stresses, we thought that, regardless of the stress acting on the plant, energy is needed. This is true not only for plants, but also for humans: if we are stressed, we are likely to run out of energy. Would a plant tolerate stresses in general by maintaining energy homeostasis?

Cotton, for example, may have to face cold early in the growing season, and later drought, heat and then again cold. Genes may be introduced and expressed for each of these stresses individually or, thinking more generically, we were led to consider energy. When we started thinking about stress tolerance at the end of the 1990s, the question was, "Are pathways in the plant switched on in stress conditions that use high amounts of energy, which, in turn, is not available for normal physiological processes like photosynthesis and growth?"

Our research strategy was to maintain energy homeostasis in our crops (cotton, canola and rice). We quickly came to consider the poly(ADP-ribose) polymerase (PARP) pathway, which had been studied in animals and humans, but not in plants. It was not even known whether plants contained PARP-pathway enzymes. PARP is an enzyme that, under stress conditions, modifies nuclear proteins like histones and protects DNA. Studies on animals showed that, regardless of the stress an animal cell has to face, PARP is induced strongly, using a lot of NAD which is a major energy-source cofactor in many biochemical pathways.

In collaboration with scientists at the University in Ghent, PARP genes were discovered in plants and the work was published in the *Proceedings of the National Academy of Sciences* (PNAS) (Babiychuk *et al.*, 1998). We wanted to test the possibility of reducing the expression of PARP under stress, thereby saving energy. We know of other enzymes that do the same, for example glycohydrolases and other nuclear proteins that are linked to one pathway that is well known. In yeast, the NAD-salvage pathway is responsible for rechanneling products made during PARP activity, nicotinamide for example, into the NAD^+ pool.

We cloned and identified the plant genes for the NAD-salvage pathway, and over-expressed and down-regulated them, which resulted in a complex picture that we published 2 years ago in PNAS (Vanderauwera *et al.*, 2007). We know now that PARP plays an important role in controlling gene-expression patterns. This is a good example of starting from one idea—down-regulation of PARP to help the plant—and ending up with a network of genes, all of which somehow play a role in the response of plants to stress conditions.

Thus, we had a pool of genes, each linked to PARP, which could be over-expressed or down-regulated to test whether the change in gene expression results in stress tolerance. In microchip arrays, we found that a number of well characterized genes responded to abiotic stress with up-regulation, those regulated by abscisic acid (ABA), for example, which play a role in stomatal control. Although these results were not surprising, this was the first proof that down-regulation of PARP in plants affects gene-expression which, in turn, results in stress tolerance.

RNA Interference

Down-regulation of genes may be achieved by various technologies. RNA interference (RNAi)—now widely used to control the expression of genes—was employed to modify the activity of PARP-pathway genes. An important advantage of this approach is that it can be highly specific. We can target the region of a gene of interest that shares homologies with other genes to down-regulate that group of genes, or the regions specific for a single gene may be targeted. Thus, RNAi contrasts with the knockout-mutant approach with which all of the gene product is lost. Often the latter method doesn't work well; some *Arabidopsis* mutants are partially lethal and the plant hardly grows, whereas, with RNAi, gene expression can be dimmed rather than eradicated. We can reduce gene expression to a certain level and even come down from 80% to 60% to 40%.

This works even better with microRNAs. All organisms have genes for microRNAs that control other genes. We isolated natural microRNA genes, replaced the region of homology for controlling the gene and put in our PARP sequence. This is even more specific and works highly efficiently. Alternatively, we used transdominant-negative mutants to change the binding sites for proteins; using a protein that competes with the natural protein, also results in a down-regulation of a given gene product, but not total knock out.

We screen the plants we produce—either by genetic engineering or by mutation—by treating with high light densities, up to 300 µE, which stress plants. We chose high light because it is easy to apply and modify. It's more difficult to apply drought stress, for example. Analysis of our PARP plants confirmed that they saved energy; they had higher levels of ADP and showed less respiration, and so were less stressed.

We are doing field trials with canola, some of which are in Saskatoon. Under drought conditions, the RNAi-PARP plants visibly grow better. They can continue to develop under moisture-deficiency conditions that curtail the growth of wild-type plants.

There's an interesting link between the NAD-salvage pathway and a well known chemical marketed by Bayer, the insecticide imidacloprid. For many years farmers observed that plants treated with imidacloprid are more vigorous and produce more leaf material. So, together with our colleagues in crop protection, we looked for links between the insecticide and our well studied NAD-salvage pathway. We found that the intermediate metabolite, fluoro-nicotinic acid, occurs in the NAD-salvage pathway and in the metabolism of imidacloprid. When we treat RNAi-PARP plants with imidacloprid, there is a combinatorial effect: they are more protected against stresses than are the transgenic plants alone or wild-type plants treated with the insecticide.

These findings have produced a new line of research. Since imidacloprid is a toxic insecticide, farmers should not use it in large quantities as a growth enhancer. However, our chemists in Germany are now looking for compounds of similar structure that are less toxic but retain the growth-enhancing effect.

Decreasing Photorespiration

Another relevant field is photosynthesis, which is less than optimally efficient because of photorespiration, whereby a third of the fixed carbon is lost. In collaboration with scientists at Aachen University, Germany, we addressed the possibility of decreasing photorespiration, thereby saving energy and improving the plant's resistance to stresses.

We cloned bacterial glycolate dehydrogenase—which converts glycolate to glycerate which then goes into the Calvin cycle—into *Arabidopsis* as a model plant, which grew more vigorously. They had larger leaves, more leaves and, even more importantly, longer roots. We are repeating this with some of our crops.

Systems Biology

Over the past decade we have dissected plants into small units, the single genes. We now have to put these together again—returning to plant physiology and plant biochemistry—to understand the interaction of all these pieces of the puzzle within the functioning plant. Changing the expression of one gene can result in changes in hundreds or ever thousands of other genes. This is systems biology, which, in my teaching, I like to compare to Sudoku. Changing one number in a stable system forces many other changes in order to achieve stability again. Similarly with genes: a change in the expression of one gene can lead to changes in expression of many others.

Thus plant-systems biology enables mathematic modeling of dynamic networks that underpin crop productivity and sustainability, and mathematics is becoming an important part of biology.

With the increasing speed of development of new technologies, DNA sequencing is getting faster and faster. In a few years, it will be easier to sequence a plant genome directly than than to draw up genetic maps, thus facilitating the systems-biology approach.

Epigenetics

As every breeder knows, regardless of whether classical or transgenic methods are used, good germplasm is a fundamental requirement, *i.e.* with broad variation in traits. Also, every breeder understands the potential role of genetic engineering, which will continue to be used in selected cases. Increasingly important is expression engineering, which includes manipulating a gene to be expressed constitutively in all tissue all of the time, using appropriate promoters. One of the most useful, in this regard, has been the 35-S promoter from cauliflower mosaic virus; however, it is now known that this approach doesn't work well for some new traits. Instead, we need to express genes in specific tissues at specific time points, and not all the time (which worked well for achieving insect tolerance from *Bt* genes). For traits like stress tolerance and improved yield, we need to be more cautious and more precisely modulate gene expression.

This is where epigenetics comes in—everything above the DNA level influencing gene expression, including well studied biochemical pathways such as histone acetylation and de-acetylation, and methylation and de-methylation of DNA, which result in changes in expression patterns.

Epigenetics may be illustrated in terms of two symphony orchestras with the same instruments playing the same piece. However, they may sound different because, for example, a trumpet player had a bad night and is playing too loudly. In other words, the music sounds different due to the change in the expression of one of the components in one of the orchestras. We can go further and say that the trumpet player's colleagues may try to compensate and play louder so that his bad playing is concealed. Although a simplification, this, indeed, happens in plants and other organisms. If the expression of one gene is changed then other genes may "compensate," to help stabilize the system.

My colleague, Mark De Block, took canola plants of a particular variety and grew them under stress and non-stress conditions and separated good performers (low respiration rate) from bad performers (high respiration rate) over several generations, producing a population with higher energy-use efficiency under stress conditions. When he had a closer look at what had happened, he found that he had selected epigenetic variants, not mutants, with DNA methylation changes that correlate with good and bad performance. These changes occurred in coding regions of genes involved in stress response. This is opening a new approach to breeding stress-tolerant plants. De Block went a step farther and combined epigenetic variants with hybrid lines. Heterosis resulted in more leaf material, and better growth under a range of stress conditions.

Second Green Revolution

We need a second Green Revolution. We now have tools in hand for a deeper holistic approach to plant breeding, looking at plants as a whole again rather than dissecting them into small pieces.

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FROM 1975 to 1980, Michael Metzlaff studied biology at the Martin-Luther University, Halle-Wittenberg, Germany, specializing in plant genetics. In 1983, he graduated with a PhD from the Institute of Genetics at the same university, researching chloroplast DNA modification.

Throughout the 1980s and the early 1990s, Dr. Metzlaff taught plant molecular genetics and genetic engineering. From 1993 to 1999 he was a senior scientist at the John Innes Centre in Norwich, UK, where his team elucidated gene-silencing mechanisms in plants. In 1999, he moved to Belgium to take up a senior scientist position at the biotech company Plant Genetic Systems in Ghent, which, in 2002, became the Innovation Centre of Bayer CropScience-BioScience. As crop-productivity group leader, with a steadily growing team of researchers and scientists, he resumed his research on gene silencing/RNAi/epigenetics and initiated studies on abiotic-stress-response mechanisms with the objective of improving stress tolerance in major crops. In 2008 he became the research liaison manager at Bayer BioScience, coordinating global research including joint efforts with leading academic universities and research institutions.

He has authored over fifty scientific publications and holds a number of patents.

Genetic Approaches to Crop Adaptation

PANEL DISCUSSION AND Q&A

MODERATOR: BRIAN FOWLER
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PANELISTS:

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Brian Rossnagel: I enjoyed all three presentations. They were well done, concise and to the point. This session is really about applying plant physiological changes in plant breeding. And plant breeders, one way or the other, have done that. One of the criticisms that I often have of some of the things that we heard about this morning is that almost every plant breeder has as a main objective achieving higher yield. And young plant breeders are often reasonably successful fairly quickly, if a decent array of germplasm is available. But, you quickly find out that you actually bred for late maturity in tall, weak-strawed plants. It depends on your environment. If you are in central United States where the growing season is essentially limitless in relative terms, that's not such a big problem. But if you are here in western Canada, or in other northern climates particularly, this can be a problem. We need to keep in mind—a good point made by Michael Metzlaff—that when you change one thing you *always* cause a cascading affect and change all kinds of other things. And usually as a young plant breeder you are really keen and you take all kinds of data, you collect all kinds of information and you do make progress. But, if you push too hard, say on one of the yield components, you may achieve that gain but you may lose in something that counts elsewhere. You also have to remember that yield is not the only criterion for a plant-breeding program. It depends on the end-product usage. For example, by significantly increasing grain size you will get that higher yield for the producer but it may no longer be suitable for his market because the particular shape of grain or its constituents may no longer be to the end-user's liking. So we have to remember that.

I recall, about 20 years ago, sitting on a panel in a lecture hall and being told by a similar group of individuals that the plant breeders in the room would not be needed within 5 years. And some of us took that as a bit of a slight. This is one large community and we need to work together. Traditional plant breeding can and will play a major significant role in delivering technologies through germplasm. Regarding Tim Sutton's work at Adelaide: the boron story is a classic in our community. It was one of the first demonstrations of the use of what I call juvenile, simple, marker-assisted selection, because that major gene is pretty simple to deal with. I would also point out that the first boron-tolerant varieties in Australia were released without anything that we would call modern biotechnology. They came from simple, plain old plant breeding started by the barley breeder back in the 1970s and early '80s. It's a great system and now, in barley at least, almost every breeding system I am aware of uses some form of molecular-marker-assisted selection. And it's all about making what we at the end of the process do more efficient in being able to utilize the germplasm we have refined.

On the drought side of things, one aspect that I found really interesting this morning is that not one of these speakers, all of whom are scientists, made any suggestion about growing plants without water. On the other hand, various persons at various levels of industry and in academia allow the media to mislead the public, in my opinion, by giving the impression that we'll somehow—through the magic of transgenics—be able to grow plants without water. I've been patiently waiting for someone to tell me that we are going to grow plants without light. This is of great concern to me because it does mislead producers and, more importantly, it misleads the people who fund research.

What the speakers talked about on drought I would refer to as "protection." If under drought conditions plants are beginning to die, if a plant can survive for a few more days and precipitation does come, that can save your crop. We see that here in Saskatchewan consistently, with barley and wheat. Barley is notorious for being a crop that, under drought stress and/or heat stress—usually drought here along with a little bit of heat—that says, "Oh the hell with this," moves to reproduction, and bang, it's done. In comparison, wheat will hang in there and fight a lot longer, probably another week, and if rain comes, an inch at the end of that week, it will yield well. However, it then is later maturing and in our environment that's a serious limitation. That's one of the things that Malcolm's company has recognized. We need to be aware of where a technology will work and where the environment will allow its expression to have a positive effect and not just sort of equal. A positive aspect is that few of the traits being looked at show negative affects in the absence of stress. It's like dealing with a bonus and selling that to farmers isn't always easy. We have all kinds of varieties that are resistant to diseases, but many farmers will take the chance of using an older, less-expensive variety because disease may not be a big problem that particular year. They may live to rue that when the disease shows up, but in a year like this in Saskatchewan disease is not a big problem. We won't have enough moisture here to have much disease.

The other thing that I want to caution people on with regard to drought and salinity is that salinity is largely salt-induced drought stress. Michael had a slide with some expression patterns, and the drought and salinity clearly had a huge amount of co-linearity, which is not surprising because the salinity effect is largely drought. But developing a barley line that will handle drought better for Australian farmers is not at all the same as developing a barley line for Saskatchewan farmers, because of differences in the growing environments. The barley in most of Australia is planted around the same time as ours is and about the time we are pushing combines through the field their material is flowering and setting seed having sat through a long period of time when it's at risk from drought and it's important that it can hang in there until it rains. However, at the end of the day, these plants may or may not be more water-use efficient. That's the real key. The material that Michael and Malcolm were talking about on the biomass side—I see that as very interesting because that may be the better use of the same amounts of nutrients, water, and obviously energy from the sun and so on to give us actually more biomass, which we can then use for the purposes that Malcolm talked about. I would suggest that where plant breeders have been most successful in grain crops, is in changing harvest index of the existing biomass. If you look at total biomass yields of most of our grain crops, they haven't changed a whole lot. We have just altered the amount we are getting off the field as grain. Despite what Malcolm said about their direction—addressing the energy end of things—I think there may be possibilities in looking at germplasm that has higher biomass—initially with lousy seed yields. Perhaps a good plant-breeding effort could move some of that into higher grain yields. If that happens, it must be due to more-efficient use of the various inputs.

The key is to think of these things as protectants. It's a matter of having plants that are more able to tolerate these various stresses, whatever they might be, and then be able to respond *if* things work out well. I like the Bayer approach in trying to reduce wasteful photorespiration. I think that C4 rice is a bit of a stretch. If you do make a C4 rice plant then it's not going to be rice anymore, and it will have the problems of growing C4 plants in C3 plant environments, and so on. But tinkering with and adjusting the wasteful photorespiration process is something that has always struck me, as a plant scientist, as something very useful to consider if you have some relatively simply inherited genetic material that can alter that and it doesn't do a whole bunch of other nasty stuff.

These things are about making plant breeding more efficient so we get things done faster. On the other hand, in terms of plant breeding, is it that critical that we do it faster? In a medical emergency with somebody dying, it's important to be fast. But as a barley or oat breeder at the University of Saskatchewan, if we produce a better variety in a slightly shorter period of time, it's probably not going to make that big a difference globally or even to local producers. The key is that we need to produce new varieties on a routine basis and keep making those improvements.

Wilf Keller: Like Brian, I found these presentations excellent. We saw some good examples from all of the speakers on the subject of gene discovery and taking forward these products, prototype plants, validation, and the implications are that these can certainly be moved into plant-breeding programs and many are already in that system. There's no question that rapid progress has been made over the last decade. I like the point made by Dr. Metzlaff on plant breeding being redefined, and I think we are going to see an acceleration of the discovery end of this whole area of plant biology. DNA sequencing was mentioned and, in fact, the cost of DNA sequencing is going down so quickly and the ability to sequence cheaply and sequence effectively in centers like Saskatoon, for example, is a reality. We can expect complete genome sequencing to become a standard protocol even for public plant breeders. How we will use all this information, I will come back to.

There are other supporting technologies. Metabolomics was mentioned. Is it possible to have biomarkers as well as gene markers for given traits? There are many new and evolving tools. Some that were not mentioned are available to breeding groups and crop improvement groups include laser-capture microscopy and high-definition transcriptomics. I'll cite the example of the Plant Biotech Institute here in Saskatoon, where early-stage embryos are excised and gene expression assessed. This has allowed investigators to identify transcription factors that affect traits such as seed size, which have been relatively difficult to work with. These are at an early stage, but I think we are, indeed, going to see a redefinition of plant breeding.

Integrating all of this new information will be a challenge. I prefer to view it not as genomics and biotech silos and the traditional plant breeding silos. This is all about modern plant breeding research and taking it through to commercialization. That integration will be critical. Twenty years ago during the biotech debate, through naiveté many of the biotech people said that the trend would to test-tube plant breeding, dispensing with traditional breeders. They felt that they could have done more with the money we were spending. We need to have integration and communication. This not about technologies that replace each other, but about plant-breeding research and we don't want to make the same error in the genomics era as in the biotech era of the 1980s. There is a tremendous opportunity to move forward in a concerted, open innovation pipeline that has plant breeding at the commercial outlet. And this will not be public versus private, but discovery research linking more effectively to commercialization and developmental research. But I have one concern at least from the overall Canadian perspective. Decisions have been made in Canada to downsize breeding programs, particularly public breeding programs. Many plant breeders have retired or are thinking about retirement and I am concerned that we may not be able to capture the value of these genomic technologies without breeders. There needs to be a public-policy re-examination about plant breeding and how significant it is, otherwise we are going to see constraints in the innovation pipeline for new varieties.

My third observation is around the broader issues, and transgenics have been mentioned. Indeed we saw examples in the work from Australia, Germany and Performance Plants showing that transgenic plants in the field have potential to make contributions. There are lots of issues around that. It's a subject for a whole conference. But we need to re-examine this in some of our key crops, particularly our small grains—wheat, barley, oats, pulse crops—that are grown here in the prairies. Are we going to ignore the use of transgenics or are we going to move forward and actually adopt them? I know that this debate has been ongoing, but I think it's time for a serious societal reexamination. A study from North Dakota State University has shown that, over the past 15 years and particularly the last 5 years, corn and soybean acreage have continually moved north and west right to the Canadian border, implying that this correlates directly with the development and application of new genetic technologies in corn and soybean. We need these in all the crops, not just corn, soybean and canola. If we want to have a diverse system of crop production and, speaking from the Canadian perspective, if we want to be competitive at the international level—because we do market high-quality products and we need to continue to be competitive—we must adopt these technologies, integrate them and, of course, market them.

John Clarke: I also enjoyed the presentations and seeing the advances in knowledge and the integrated approach to this research that is making rapid progress. Now, as a wheat breeder, I've been excited by the potential for marker-assisted selection for probably 20 years, and I think it's now coming to the point at which we are actually applying marker-assisted selection particularly for simply inherited traits that would otherwise be difficult and expensive to measure. For example, we are making rapid progress in durum wheat with low cadmium-accumulating varieties. But not all crops receive similar investments in biotechnology and supporting research. Although wheat is grown worldwide, the research is very much in the public domain, relying on the whims of politicians and we seem to be unwilling to make the necessary investments required for crop improvement.

Following up on some of the comments that Brian and Wilf made, the integration of these research efforts is extremely important and, as scientists, we've recognized that for a long time. Certainly recent advances reflect the importance that we have placed on integration. However, at the political and science-management levels, there is a tendency to seize upon the more attractive or "sexy" aspects of research, therefore, the integrative approach isn't necessarily funded as well as it should be. This translates not only into the actual practical research, but also to the training of graduate students and right now we have a real deficit in terms of new plant breeders. The low numbers of graduate students coming into universities and agricultural colleges who are interested in pursuing plant breeding are shocking. As we try to replace retiring plant breeders in Agriculture Canada and other agencies in Canada, we just can't find qualified people to step into these important positions. So we have to keep in mind that training and emphasis of research dollars to support these activities is very important.

The pace of change is becoming very rapid, due to advances in DNA-sequencing technologies and we are at the point where we can sequence or map populations very quickly. Tim Sutton showed that significant effort is needed to develop the necessary phenotypic information to make practical use of that information. I can't imagine screening 5,000 RILs[1] over the number of environments that that group has managed to do, and, again, this comes back to how funding is applied. The phenotyping aspects have been seen as less important in the process up until now, therefore we don't have a lot of phenotypic information that can be used to take advantage of the sequence information that we can now generate.

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[1] Recombinant inbred lines

Brian Fowler: We are going to open up for questions for the panelists and also the speakers. I have one quick querie while people are thinking about how they are going to phrase their questions. In all developmental programs, you need leadership and traditionally in variety development plant breeders have been providing the leadership. In this new integrated system, who should take on the leadership? The biotechnologist or the plant breeders? What kinds of change should we be making? I think that's very important because, if you don't have leadership, you are not going to have any direction. Anybody want to take a crack at that?

Malcolm Devine: I work in a small organization where we have everything from basic gene discovery at the front end through to validation in the crop. We are not a seed company. Neither are we a plant-breeding company. We don't introgress our traits into finished varieties or hybrids. Unless you are a basic gene-discovery scientist funded to do that kind of work, it is essential to have what you might call a product concept. What do you want to come out of this at the end, to be introduced? Certainly if you are in a commercial organization that is what you think about, and many of the breeders I know working in the public sector are thinking about commercialization: what traits do farmers need and what new traits and new varieties will farmers pick up on to help their productivity, profitability, *etc*. It's important that there be a clear product concept. In my experience, someone at the back end of the process—the plant breeder or agronomist—ultimately should call the shots about what goes forward and what doesn't. All research companies comprise people with strong wills. You have sales people who want to sell hybrid canola in the field. You have plant breeders who want to develop the best germplasm possible. But, at the front end, you have scientists who want to develop new technology and push it. And there's always this struggle between technology push and pull. Having the push from the scientists bringing new material and new ideas in is good because it can, if they are successful, invigorate and add substantially to breeding programs. But ultimately, if you must pick someone to be in charge—and I think it is helpful to have one person or group in charge—it should be those who are responsible for developing finished varieties.

Michael Metzlaff: I agree with Malcolm. It has to be the breeder. But, even as a molecular biologist I would call myself a breeder. We have new tools that we can give breeders. What we may need in the future is a new—how shall I say, I have to be cautious—a new type of breeder who has a lot of knowledge in molecular biology as well understanding of what is going on in the laboratory. Breeders and molecular biologists speak different languages and often don't understand each other. We have to change that to be successful. But the leader has to be the one who knows what the farmer needs, what the product should be, and we can help with the enormously useful tools of new technology.

Tim Sutton: In Australia we have been reasonably successful in promoting and building a team of the new type of breeders, to use that term. Most of the young breeders coming through now are well trained in molecular biology. They have skills in classical plant breeding and know a lot about molecular biology too. They will achieve technology integration. Our system for funding applied research is very much driven by breeders and farmers. If you are a farmer in Australia and you grow a grain crop you pay a compulsory levy on the farm-gate value that goes into a fund that's distrubuted to research organizations to work on problems that are relevant to cropping, and farmers have a big say in that. Breeders are involved in the discussions with farmers that decide where that research investment goes. The breeders definitely should drive a lot of what the molecular biologists work on.

Metzlaff: I forgot to mention that molecular biologists have to know breeding, and that is missing. When I studied plant genetics in the 1970s, it included a lot of breeding and I still gain from that. I still know what breeding is. But then, since the 1980s and '90s the new type of plant molecular biologist doesn't know a lot about breeding. So, to be fair, it has to come from both sides, otherwise it will never work.

Keller: Having a targeted program, led by a benign breeder, is acceptable. But, bear in mind that there has to be a discovery element, that creativity, to keep injecting new ideas. They may not fit the target that the breeder has at a given point in time, but certainly the team leader must include discovery research. Otherwise we are going to be in a mess 25 years down the road. Certainly you need to have that teamwork, but here in Canada our breeders are overloaded. I don't think they have the time to provide that leadership because they are running too many programs. We haven't strengthened the breeding programs to the extent that they require. That's an issue as far as I'm concerned.

Fowler: Do either of the plant breeders want to make a comment or do you want to quit while you are ahead?

Rossnagel: We haven't had a lot of experience in this part of the world with private breeding programs until the last two decades with canola, but most of the successful breeding programs have involved teams. As someone said, breeders seem to get the recognition because they are the ones who release the varieties that everybody gets excited about and makes money on. But, in any team, you need leadership and benign leadership is sometimes useful and sometimes less benign is useful. A key issue is understanding the differences between growing a plant and growing a crop. People who just grow plants in pots often don't appreciate how different it is growing a whole group of plants. I would agree with Tim that our Australian friends have done a pretty good job of training plant breeders who have dual experience. We have been trying to do that in our institution as have the University of Manitoba, Guelph and others. But, the fact is, many of those new breeders are very good on the molecular side, whereas traditional plant breeders who have been around for a while see slippage in understanding field and farm aspects. We now have graduates who have excellent training in molecular genetics, although sometimes I wonder how much they understand of Mendelian genetics, which is the key. So you end up with folks who handle *Arabidopsis* real well, but don't appreciate it when somebody says, "Yeah, but that doesn't really matter when you get to the field."

Darby Harris (University of Kentucky): Tim, did you screen for the *Bot* mutation in a high-boron system?

Sutton: Right. The *Bot1* gene that provides tolerance to high levels of boron comes from the land race 'Sahara' and it's a naturally occurring tolerance mechanism. That's an important point, especially when you think about application to breeding. We screened about 7,000 plants. It's basically a process of elimination where you have a large marker interval and you saturate that with markers and you eventually walk your way in using a technique called progeny testing, which tells you the direction of the tolerance locus from a certain recombination point. And you end up walking into an interval that corresponds to the maximum amount of recombination you can get from the size of your population.

Harris: Okay, and there may be a number of genes in there, but then you look at candidates?

Sutton: Right. Then you can use either of two approaches. You can then look at the syntenous region in rice, which is where rice really comes in handy and you can ask the question, "What genes are located in that syntenic interval in rice?" If your interval is small there may be three. If it is large there may be 500. Are any of those good candidates? In the case of the *Bot1* story, the gene is not located in a syntenic position in rice, so the neighboring genes in that interval in rice are present in barley, but there is nothing that correlates with our *Bot1* gene. So, we ended up cloning *Bot1* using a forward genetics approach combined with candidate gene-reverse genetics.

Harris: Okay. I may not have gotten this right. Once you determined which gene and then you sequenced it, you noticed a couple of different nucleotide variations, one in the transmembrane and one mutation in the cytosolic. But that wasn't really what was giving Sahara its boron tolerance—.

Sutton: It's really two fold. There are nucleotide differences between the Clipper and Sahara alleles, and we have shown that they affect the ability of the protein to transport boron, at least in a model system like yeast. But then there is the other side—the gene is also much more highly expressed in the tolerant genotypes. So there's polymorphism and there are differences in expression that overall translate to the tolerance that you see in Sahara.

Harris: Malcolm Devine, I'm interested in the allele for increased biomass. You showed a nice video where not only was the *Arabadopsis* inflorescence meristem delayed in coming out, it seemed to me like it might be a delayed flowering that led the *Arabidopsis* to stay in the vegetative state. Because I'm in a cell-wall lab, I've come across this and tried to note the mutations that cause that. I know that the FLC[2] locus was one of the originals. In a few other cases, transgenes have increased biomass. Are you at liberty to say whether you generated that via a transgene or a mutation?

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[2] Flowering locus C.

Devine: Yes, it's a transgene, but I cannot be very specific in my answer. You mentioned FLCs, so you know the network of flowering loci, *etc.* This gene is associated with them and our assumption is that it plays a role in that same pathway. And, you are right, it governs the transition from vegetative to flowering with over-expression of the gene in this case. Of the different examples I showed, by the way, some were down-regulated, some were knockouts, some were over-expression. I didn't identify them as I went through the talk, and perhaps I should have, but, in this case, it is an over-expression of one of those regulatory genes. It's a down-regulator in that network of genes, a transcription factor, and by over-expressing it you delay the transition.

Dan Pennock (University of Saskatchewan): My question has to do with the higher incidence of extreme events, drought, precipitation, flooding. Some of the issues we heard are present at the start of the growing season like salinity or boron, whereas drought or heat or flooding are events that cannot be predicted over the long term. Brian raised the point that we are developing products that will require premium pricing, to provide protection in situations that farmers don't know with certainty will occur, but will probably increase in frequency with climate change. Is there a reason to believe that farmers will pay a premium price for something geared to one specific issue, like drought or heat, when, in fact, there could be a gamut of climate-induced changes that may affect crop production?

Devine: If it's a single extreme, almost catastrophic, event, you can put all the genes in the world into that plant and it won't help. If you have no rain for 18 months, I don't think you can grow a crop. You can't get something out of nothing. You are right in what you are alluding to, and Brian's comments earlier were correct. There are no miracle genes. All genes have small, incremental effects. It will be hard to protect plants against massive climatic or weather events. Maybe provision of flooding tolerance will be possible, and some interesting work is in progress on that. About 6 or 7 years ago, when I was still working for Bayer in Belgium on the stress program that Michael talked about, we were talking one day about the competition in this area. The usual suspects came up—Monsanto, Pioneer, *etc.*—and someone based in the United States said, "Crop insurance." He was absolutely right. Crop insurance is the competition. A farmer may pay more for a better variety from Bayer or someone else or take out a better crop-insurance policy. That was a reality check. It made us think what the value of the trait is because now we had something to compare it to. If you are introducing something completely new into the market place, you don't know where it should be priced. Was the first IPod worth $1,000 or $50? If there is something you can benchmark against, then you can estimate your price range and work back to see if it is actually worthwhile. That Bayer and others are still working on this suggests that they have done the business calculations and it is worthwhile. But, they are looking at traits on a crop-by-crop basis. Bayer, Monsanto and the others specialize in a few major crops. They're not going to put a drought trait into all crops. They will put it into those in which it will have most value, which correlates with most benefit to farmers. It may not be marketed in all regions. Cotton is grown in some rain-fed regions and some dry regions. From the contact I have with seed companies, they are looking for traits that will increase average yields over time. For example, a new trait in corn marketed in the Midwest might have an average yield benefit of 5%, recognizing that in some years it will be zero, in some years it will be 2% and hardly measurable, and in some years it might be 10%. A marketing package will be developed to show farmers that, although they won't need this every year, over time it will benefit them.

Fowler: I'd like to bring Brian and John into this discussion because they have very practical experience with catastrophic events on a regular basis. One I can think of is early fall frost, and as plant breeders you are dealing with the question of maturity all the time. Brian, you have developed early maturity varieties. What's your opinion on the tack that would be used or the reaction of farmers to these things"

Rossnagel: Steve Shirtliff is an agronomist in our department, and he and I work together on the oat program. He is doing a lot of innovative things on oat, which is one of those lost-in-the-hinterlands crops. Few work on it. Herbicide companies don't even try to develop herbicides that will work on it. One of our major issues is wild oats as a weed and Steve has done a lot of work on that. We go out to farmers' meetings and one of the question that often comes to him is, "You've talked about how to manage my 100 bushel to-the-acre oat crop, and that's good, but lots of times I get 60 bushels." and Steve's response, and it's the most correct I've ever heard, is, "That's what crop insurance is for." Because at those sorts of yield levels in today's agricultural system in Saskatchewan, and western Canada in general, there is nothing you can do management-wise. Perhaps irrigation would solve it because it's almost always drought that creates that problem.

As Brian indicated, we've released some extremely early-maturing barley varieties that can be planted very late. We released those for situations like this year's; farmers who spent a fortune trying to grow canola have already lost it, and then last weekend we got an inch and a half of rain so they could actually replant. However, if they plant canola, they are going to spend a lot of money again and the probabilities of harvesting a good-quality crop and getting a good price are low because of the maturity issue. These barley varieties are cheap to plant and can produce decent yields within that narrow window. We had absolutely zero uptake of those varieties by farmers because, when they go to plant in May at the normal time, they don't expect to need them. There was no incentive in the seed-production business to produce that seed because most of the time they won't sell it. I've had phone calls in the last couple of weeks requesting those particular varieties and my answer to them is, "It doesn't exist because you didn't buy it before."

Bruce McPheron (Pennsylvania State University): Those of us in the US land-grant system, directors of research and experiment-station directors, meet annually and a perennial topic on our agenda is whether we can continue to afford investing in the facilities that preserve our plant-genetic resources. Part of the money for that support comes out of our budgets, and it perennially becomes a discussion of the pipeline for plant scientists and for plant breeding in general. And so, I would turn to a broader question: "Is it possible that climate change provides the imperative for a reinvestment in the plant sciences and in plant breeding efforts in particular?" I'm struggling with this because, clearly, the traits we have been focusing on don't seem to be sufficient to capture the attention of decision-makers and funders in providing that investment, particularly in the public sector. The private sector has found an excellent business model with selected crops, but we've all agreed that there aren't enough crops included in the portfolio. Then again maybe we will be asking this question again next year when we are at Davis and the topic is diet, nutrition and health. Will that be the imperative that will lead to an expansion of investment in the plant sciences? Perhaps that's rhetorical at this point, but is it something we should come back to as an overarching consideration? Is there something about the drama of response to this issue that we can seize upon to guide investment?

Fowler: Is there a response to those comments? It was mentioned to be rhetorical but certainly important.

Metzlaff: I'm an optimist. I think things are changing already. When I gave talks in the past on transgenic traits—herbicide tolerance, *Bt*, *etc*.—laymen in the audience saw little need for them. But, now when I speak about drought tolerance and yield, things like that, people are much more attentive. We can bring things forward only if need is perceived in the population. Everybody sees that climate change is occurring. Everyone who has a garden sees that summers are hotter. People are starting to listen and think, "Yes. This is something that we may need in the future." But maybe that's the optimistic view.

Devine: There is a tremendous case to be made right now for more investment in this area. Plants underpin all aspects of life on earth. You said your meeting next year was on food, health and nutrition. What's behind all of that? Plants. So, investment in plants is as important as ever. And preserving existing genetic diversity is incredibly important. And I say that as a biotech person. Without a strong base of natural genetic diversity, we have nothing.

Rossnagel: Molecular genetics provides new capabilities for evaluating germplasm collections. I have the world collection of oats sitting at the Canada Research Center right here. As an oat breeder, I have gone there only two or three times, but only as a last resort because it's so hard to figure out which is the best line to choose. We have some incredible tools now to do association mapping, and so on, that 5 years ago were impossible. The only way to do that was to grow out the 21,000 lines that we have and look at them. Sadly, we will probably find out these collections aren't as diverse as we think they are.

George Wagner (University of Kentucky): Dr. Devine, your comments about the Indonesian work that seemed to focus on night temperature remind me of the fact that my agronomy colleagues tell me that the highest corn yields are obtained on the Colorado plateau if they are irrigated, because of optimal day temperatures and the cool nights. Are we focusing on root respiration here?

Devine: I would have to go back and read the publication that I was referring to. Whether it's root respiration or above ground, I don't recall reading it. I'm sure it must be in there. It was a PNAS paper of a year or two ago.

Metzlaff: And we don't know yet in our work with photorespiration. We don't have the link to yield yet, although we see biomass increase.

Wagner: But have you expressed roots versus leaves?

Metzlaff: Not yet. We will do that.

Mark McLellan (University of Florida): I want to make a comment about the conversation regarding plant breeders and gene jockeys. I enjoyed that because it's happening every week in my organization. I know that many other schools are really struggling with this. We struggle with it at the top level, the department-chair level and we struggle with it mightily at the faculty level. As director of the experiment station, for the past year I have worked hard to build a marriage between my biotech folks and my breeders. I have about twenty breeders in my organization and going back over a couple of decades, of course, the breeders were the main show and biotechnology was coming on strong, we were building that capacity. Now as state funding is reduced and we are in the hunt for dollars, the breeders struggle mightily to bring in external grant dollars. Biotechnologists seems to grab that pretty fast, so there are dynamics there. The only counterbalance to that is royalty flow. Finally we are in a game where we have millions in royalty flow, which really are making a difference. But still, I am a food scientist by training and this reminds me of the difficulty food scientists and nutritionists have. We speak different languages. We don't even understand what each other is talking about and often we are in the same department. I find that same situation with my breeders and my geneticists. I have attempted to bring those two organizations together, and asked them to consider a marriage, and they said that they'd rather just date. They don't see eye to eye. And so, we are in the hunt for solutions. My latest attempt is to put a pile of money in the center of the table and say, "You can get to that, but only if you come hand in hand. If a gene jockey and a breeder work together then they can tap these funds." And that seems to be getting some traction. On behalf of all the universities, we are open to ideas here because I do believe the next-generation breeder has got to be someone special. Not traditional. And yet the comment was made about slippage. We *are* seeing slippage in skill sets. Again, we are open for ideas and answers.

Module 3: Other Approaches to Adaptation

Table of Contents

Living With It: Adapting Crop-Production Systems to Emerging Climate Change

Donald Smith
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This paper presents an overview of challenges facing agriculture as a result of developing climate change and discusses adaptations the agricultural sector will need to make to meet these challenges. It provides a summary of:

- potential climate changes that could affect crop-production activities,
- characteristics that make a crop better able to adapt to climate change, and
- changes to crop production that are likely to occur in response to climate change.

Expected Changes in Climate

Global climate change is well-documented and generally accepted (IPCC, 2007). Atmospheric carbon dioxide (CO_2) levels, strongly linked to climate dynamics, have been steadily increasing since the onset of the industrial revolution. This increase is widely regarded as a major etiological agent of increasing atmospheric temperatures based on the heat-trapping capacity of CO_2, the "greenhouse" effect. Releases and atmospheric concentrations of other, more-powerful greenhouse gases (GHGs), such as methane (CH_4) and nitrous oxide (N_2O), have also been rising, contributing to ozone depletion and increasing temperatures (IPCC, 2001).

Climate change will cause increasing average atmospheric temperatures and evaporation of surface water (Zhang *et al.*, 2000); increased incidence and periods of drought (Kerr, 2003); and an increase in incidence of other extreme weather events (Rosenzweig *et al.*, 2001; Kerr, 2003). Each of these emergent and interacting factors poses significant challenges to our current agricultural systems' infrastructure and management practices, threatening our national and global food supplies.

Global temperatures are expected to increase by 1.5 to 4.5°C over the next 100 years (Vaughan *et al.*, 2001). Canada, at its high latitudes, has already experienced more climate change over the last 100 years than have most countries (IPCC, 2001; IPCC, 2007).

The mean annual temperature within Canada has increased 0.5 to 1.5°C during the last century (Zhang *et al.*, 2000) and is expected to increase by 3 to 5°C over this century (IPCC, 2007), with increases on the order of 8°C at the most northerly regions, reflecting a general trend for high latitude areas to show greater temperature increases than more-equatorial areas. In addition, night temperatures have been shown to be increasing at greater rates than daytime temperatures (Easterling *et al.*, 1997) and winter temperatures are increasing more than summer. Although some areas are expected to have greater precipitation, others will generally become drier (Kerr, 2003) due to reduced precipitation, increased evaporation resulting from increasing temperature and extended periods with unfrozen water in northern areas. Simulation models predict an increase in evaporation of 2 to 3% for each 1°C increase in atmospheric temperature (Lockwood, 1999). However, this effect may be moderated by increased cloud cover (Ohmura and Wild, 2002). In general, precipitation is predicted to increase at higher latitudes, but decrease by about 20% in most subtropical areas (IPCC 2007). Mendelsohn (2000) indicated that global precipitation may rise by 7% with a global temperature rise of 2°C by 2100.

Observational data and output of twenty-three global-climate models indicate that, by the end of 21st century, growing-season temperatures will exceed the most extreme seasonal temperatures recorded from 1900 to 2006 for tropical and subtropical areas (Battisti and Naylor, 2009). Anthropogenic warming of the Indian Ocean disrupts onshore moisture transport, reduces rainfall and creates drought for countries dependent on rain-fed agriculture. Current tendencies could result in a 50% increase in undernourished people by 2030 (Funk *et al.*, 2008).

Increasing temperatures are also responsible for rapid shrinking of glaciers, which are vital sources of river water used for irrigation of large agricultural areas. In Canada, the Peyto glacier in Alberta, which supplies river water used to irrigate neighboring prairie crops, has lost over 70% of its mass during the last few decades (Demouth and Pietroniro, 2003).

Melting of glaciers and polar ice will also result in increased sea level, threatening to submerge coastal areas, some of which are highly populated and maintain very productive agricultural land, with Bangladesh being the best example. A number of island nations will be at extreme risk. Sea levels are predicted to rise on the order of 50 to 100 cm by 2100 (Gregory and Oerlemans, 1998; IPCC, 2007), the effects of which will be exacerbated by more-frequent, larger coastal storms.

Climate change is expected to increase the incidence of extreme weather events (IPCC, 2001; Rosenzweig *et al.*, 2001; IPCC, 2007), such as drought, heat waves, and heavy precipitation and floods, making crop production more unpredictable and difficult. Wind speeds are also expected to increase due to an increased heat flux from the equator to the poles, resulting from increased temperature, increasing the potential for wind erosion of agricultural soils. Increased temperatures and intensive rains will accelerate the breakdown of soil organic matter, increasing nutrient leaching and soil erosion (Smith and Almaraz, 2004; Lotze-Campen and Schellnhuber, 2009).

Much of the climate change currently being recorded is attributable to the continuous increase in GHG emissions, most notably CO_2. This increase in atmospheric CO_2 concentration will have direct and indirect effects on crop plants, not all of them negative; CO_2 is often a limiting resource in plant canopies, and it is expected that an increase in CO_2 will generally increase plant productivity and water-use efficiency by reducing stomatal aperture and/or number per unit leaf area (Drake *et al.*, 1997; IPCC, 2007).

Crop Plants and Climate Change

Studies of climate-change impacts on crops have been largely confined to simulation models (Challinor *et al.*, 2009), and there is a need for empirical data regarding the relationship between climate trends and yield variability of major crops.

Climate change is already affecting many organisms (Jensen, 2003), impacting photosynthesis, water use and movement through the landscape, and distributions of crop and pest species. Temperature and CO_2 increases are expected to boost plant productivity and yields of crops like wheat, rice and soybean (Lobell and Asner, 2003), though this is not seen with small-grain cereals, important components of Canada's agricultural industry, which show accelerated development and decreased yields in response to increased temperature (Batts *et al.*, 1997). In high-latitude areas, the growing season is roughly defined by the time between the last killing frost in the spring and the first in the fall; these frost events invariably occur at night. Greater increases in nighttime than daytime temperatures are expected to lengthen the growing seasons more rapidly than average daily temperatures. This will result in an ability to produce crops and crop varieties requiring more thermal-time for maturity. Climate warming will also allow production of new temperature-sensitive crops, such as fruit and nut trees in more northern locations than currently, for example in southern Quebec and Ontario (Bélanger *et al.*, 2000). However, higher nighttime temperatures will also increase the rate of consumption of photosynthates through respiration, potentially offsetting some of the increases due to longer growing seasons (Smith and Almaraz, 2004). Warming of 1 to 2°C at low latitudes is likely to produce a negative responses for crop growth and yield and small beneficial response at higher latitudes (Easterling *et al.*, 2007).

Drier conditions will result in greater drought stress for crop plants (IPCC, 2001, 2007). Plants will likely respond by reducing stomatal aperture and/or number of stomata per unit area of leaf, decreasing water loss through decreased evapotranspiration; however, this will also decrease photosynthetic rates (Flexas and Medrano, 2002). Potential losses of photosynthesis from reduced stomatal opening may be offset by increases in atmospheric CO_2 levels. This will, however, also increase average leaf temperature as a result of reduced evaporative cooling from the leaf surface. Increased CO_2 levels have been shown to increase root-C dry weight, and plant responses have been observed to involve increases in the size of root systems, facilitating water acquisition and retention (Kimball *et al.*, 2002).

Yields of most agricultural crops increase under elevated CO_2 concentrations; productivity increases are in the range 15 to 25% for C_3 crops (wheat, rice, soybean) and 5 to 10% for C_4 crops (maize, sorghum, sugar cane) (IPCC, 2007; Lotze-Campen and Schellnhuber, 2009). The former will likely benefit through increased productivity as photorespiration losses are reduced, whereas the latter are not expected to show such benefits, at least not as substantially. However, C_4 plants may receive a competitive advantage under warmer, drier conditions, as they generally have higher water-use efficiencies, making them more adapted to these conditions. Climate change will, therefore, affect competitive interactions between C_3 and C_4 plants and, by extension, crop-weed interactions (Kimball *et al.*, 2002; Lotze-Campen and Schellnhuber, 2009). Which photosynthetic type benefits more will depend on the interaction between water and CO_2 availability, and so will be site-specific.

Although increased atmospheric CO_2 has the potential to increase plant photosynthetic activity, the nutritional quality may be negatively impacted by shifting carbon:nitrogen ratios, leading to reduced protein levels and increased amounts of starch (Conroy *et al.*, 1994; Jablonski *et al.*, 2002) limiting potential benefits from increases in plant productivity.

Nitrogen fixation has been observed to increase with rising CO_2 (Ińaki De Luis et al., 2002) and may increase under drier soil conditions due to improved water-use efficiency under elevated CO_2 levels (Yu *et al.*, 2002).

Increased productivity of crop plants due to increased CO_2 levels may force corresponding increases in fertilizer demand, in order to achieve higher yield potentials. However, nitrogen-use efficiency is reportedly higher under elevated CO_2 levels (Prior *et al.*, 1998), potentially mitigating increases in fertilizer demand. Application of plant-growth-promoting rhizobacteria (biofertilizers) and understanding signaling between bacteria and crop plants may also lead to improved plant productivity and, as a result, increase soil-C storage and reducing potential; some of these signals also have the potential to increase legume nitrogen fixation, reducing nitrogen-fertilizer applications in the long term and, therefore, reducing nitrous-oxide emissions (Mabood *et al.*, 2006).

Enhancement of plant growth in response to increased atmospheric CO_2 levels will also improve plants' capacity to respond to pests and pathogens by providing additional resources to mount defense mechanisms (Street-Perrott *et al.*, 1997; Smith and Almaraz, 2004; Lotze-Campen and Schellnhuber, 2009).

The northerly migration of pest and weed species in response to warmer conditions at higher latitudes has already been documented (Walther *et al.*, 2002; Ziska and Runion, 2007) and poses serious challenges to growers unfamiliar with their management. Insect pests may also increase their numbers of generations produced *per annum*, thereby increasing insect densities and associated predation of crops. Temperature rise and elevated CO_2 concentration could increase plant damage from pests in future decades, although only a few quantitative analyses exist to date (Easterling *et al.*, 2007; Ziska and Runion, 2007). Weeds show a larger range of responses to elevated CO_2 than crops due to their greater genetic diversity (Ziska and Runion, 2007). Furthermore, increased wind speeds will facilitate the dispersal of disease spores.

Soil-C stores are expected to decline as increased temperatures promote microbial activity and the breakdown of organic matter (Anderson, 1991; Smith and Almaraz, 2004; Lotze-Campen and Schellnhuber, 2009). This phenomenon is expected to be most pronounced in arctic and sub-arctic regions where organic matter remains in soils for long periods of time due to temperature-limited microbial activity. However, increased allocation of C to plant-root systems in response to increased CO_2 levels may offset these losses (Suter *et al.*, 2002). The increase in root mass may also benefit mycorrhizal fungi and increase the production of glomalin, a glycoprotein produced by endomycorrhizae that contributes to soil aggregation, thus mitigating soil erosion resulting from higher wind speeds and drier soil conditions (Rillig *et al.*, 1999).

Timing of heat stress is critical for crop development. For example, high-temperature stress during grain filling of chickpea, canola and mustard resulted in greater losses of yield than during the flowering stage (Gan *et al.*, 2004; Wang *et al.*, 2006). In Mediterranian rain-fed regions, chickpea grain yields were 50 to 80% greater with early planting (late autumn, early to mid-winter) because of a longer vegetative period, extended flowering and maturing phases and better environmental conditions (Lopez-Bellido *et al.*, 2008).

A Canadian study (Almaraz *et al.*, 2009) showed that sorghum could do well in Canada under climate-changed conditions. Sorghum is known to produce an extensive root system early in its development and to close its stomata quickly when faced with increasing water deficit. A study in Uzbekistan (Bourgault, Madraootoo and Smith, unpublished data) showed that mung bean is considerably better at handling water deficit than common bean due to its higher root:shoot ratio and restriction of water loss through stomatal control. Together, these studies suggest that larger root development, for better soil-water access, and stomatal restriction of water loss are two important elements of crop adaptation to drier conditions.

An evaluation of drought stress on dry-bean cultivars in the United States demonstrated reductions in yield and seed weight of 60% and 14%, respectively, with a 4-day increase in growing season (Singh, 2007).

Production-System Adaptations to Increasing Atmospheric Temperatures

Crop development and total agricultural production depend directly on climatic factors, such as temperature and precipitation, and will, therefore, be directly affected by climate change (Salinger, 2005; Lotze-Campen and Schellnhuber, 2009). How emerging climate changes will impact agricultural production is difficult to predict and remains uncertain (Lobell *et al.*, 2008; Challinor *et al.*, 2009).

Rising atmospheric temperatures will have both direct and indirect consequences for crop plants. Greater heat stress will likely be experienced more often by temperate-adapted species, potentially reducing their photosynthetic efficiency and increasing their susceptibility to pests, disease, and competition from weedy species (Garrett *et al.*, 2006). This will probably result in a need for more-frequent pesticide applications, more-careful pest monitoring, and development of pest-resistant crops.

Climate-change conditions will affect crop yields and may require changes in the types of crops produced in a given area. Increased spring and winter temperatures will increase the length of the growing season in Canada, increasing agricultural production with the introduction of new varieties and species of crop plants that demand longer periods for maturation than are currently grown. Warmer autumn conditions in Quebec are already leading to a longer growing season (Almaraz *et al.*, 2008) and simulation models predict an increase of 30 to 45 days in growing-season length by the end of the 21st century in the main agricultural regions of Ontario and Quebec (Bootsma *et al.*, 2004). In contrast, in the United States, corn and soybean yields decreased in response to increased growing-season temperature, with an observed reduction of 17% for each degree Celsius increase in average temperature (Lobell and Asner, 2003).

Northern nations, such as Canada, are expected to have the most drastic changes as higher latitudes see greater temperature increases relative to equatorial regions (IPCC, 2001). For example, over the past three decades, Quebec's Monteregie region has seen a general trend of increasing temperature, with the greatest change in the growing season occurring at the end of the season (September) where a mean increase of 2.8°C has occurred, whereas precipitation levels have shown no significant change over the same time period. An increase in average corn yields of 118 kg ha^{-1} $year^{-1}$ was observed between 1973 to 2005, and was explained, in part, by the increased September temperatures (Almaraz *et al.*, 2008).

Earlier springs may allow earlier planting of low-temperature-sensitive crops, early maturing and harvest, and possibility of double-cropping practices, which could greatly increase total productivity in parts of the northern hemisphere (Lotze-Campen and Schellnhuber, 2009). Lengthening of the growing season may also bring grain-corn production to areas of the United Kingdom where it is currently too cool (Kenny, 1993).

The productivity of C_3 plants is expected to increase in response to increasing CO_2 and this will mitigate energy losses associated with photorespiration (Kimball *et al.*, 2002). Increasing temperatures are likely to reduce stomatal aperture and duration of stomatal opening, a response to increasing leaf evapotranspiration through cuticular water losses. This is expected to increase the water-use efficiency of C_3 plants, which may make them more adapted to agricultural areas that experience decreased water availability through increased temperature, reduced rainfall, and/or reduced glacial runoff.

Warmer conditions on the Canadian prairies may allow production of winter wheat in areas where this was not previously possible. At higher latitudes, yields of winter wheat are generally higher than those of spring wheat. In part, this may be because they resume growth almost as soon as the snow cover has gone, enabling exploitation of soil moisture resulting from snow melt. One must wait until the soils become sufficiently dry to seed spring crops. The earlier development of winter cereals may also allow them to escape potentially hot and dry mid-summer conditions of a climate-changed world.

Traditional breeding programs should focus on selecting and optimizing heat-tolerant genotypes to replace current varieties. Molecular-genetics research will also play an important role in identifying specific genes associated with stress tolerance (Goswami, 2006; Lotze-Campen and Schellnhuber, 2009). Several specific targets for genetics-based adaptation of crop plants to emergent climate change include (Smith and Almaraz, 2004):

- increasing length and rate of development of plant-root systems;
- increased ability for osmotic adjustment in response to dry conditions;
- quicker stomatal closure at the onset of moisture stress;
- stronger responses to abscisic acid (ABA), which mediates many responses to drought;

- increasing water-use efficiency; and
- reduced cuticular and stomatal transpiration.

Identification of genes associated with these characteristics may lead to the development of genetically engineered cultivars much better adapted to emergent climate change.

Some tillage systems need improvement; for example, lower spring soil temperatures associated with no-till currently limit early crop development in much of the St. Lawrence Lowlands of Quebec (McRae *et al.*, 2000). No-till systems will become more feasible as conditions warm, allowing more sequestration of C in soil, better retention of water in soil, increased crop response to nitrogen fertilizers leading to reduced fertilizer application, and decreased soil erosion (Smith and Almaraz, 2004; Almaraz et al., 2009; Lotze-Campen and Schellnhuber, 2009).

Average precipitation levels have increased by 5 to 35% over the past three decades in Canada (Zhang *et al.*, 2000). However, net evaporative demand is also increasing and in some areas the increased evaporation will outstrip increased rainfall, leading to drier conditions. Nevertheless, in general, the outlook for Canada, with regard to climate change, is much better than for most of the world.

In temperate regions where conditions become hotter and drier, production of C_4 crop plants could be expanded as a way to adapt. C_4 plants are naturally more suited to these conditions than C_3 species (Ainsworth and Long, 2005) making them more tailored to emerging climate trends.

Indirect impact on crop plants will involve ecosystem changes as species composition is altered, both through emigration to the north and immigration from the south. Also, migrating populations of invasive and endemic species will need to be managed.

Need for cultivars with high pest and disease resistance will increase as new pests and pathogens migrate northward into Canadian agricultural areas. Genetic engineering of crop plants may be of assistance. Monitoring of pests currently existent just south of the border, and quarantine measures, should also be undertaken.

Adaptation strategies to climate change include:

- altering varieties with increased resistance or tolerance to heat and drought stress and altering the timing of planting or location of crops;
- adjusting fertilizer rates; and
- use of technologies for water preservation and integrated pest management.

Adaptations are efficient if costs of implementation are less than the resulting benefits (Mendelsohn, 2000; Howden et al., 2007; Lotze-Campen and Schellnhuber, 2009).

There is evidence that past climate shifts have caused social disruptions (Hodell *et al.*, 2001) including human migrations. In North America, there will be a northward migration of crop production (Smith and Almaraz, 2004). For instance, the Palliser triangle may became too dry for annual crop production, whereas more northerly areas of the Canadian prairies will become warm enough for crop production (Faculty of Agricultural and Food Sciences University of Manitoba, 1994; Smith and Almaraz, 2004). A northward movement of agricultural activities will require the development of rail infrastructure in the

Canadian north. At the same time, as conditions warm, it may become more feasible to ship larger amounts of grain from the port of Churchill (Smith and Almaraz, 2004). Current public policies promote the production of established crops in given areas. We need new, more flexible policies that allow the introduction of new crops and cropping practices that are better adapted to a climate-changed world (Smith and Almaraz, 2004).

Dynamic adaptation policies are necessary. Areas where adaptation policies have to be further developed are water management and distribution, optimization of land resources, carbon credits, management in agriculture including implementation of new technologies and changing of agricultural practices, government programs supporting carbon credits and trading and promotion of sustainable agricultural systems.

Studies of cropping systems indicate potential benefits from management adaptation under warming conditions and increased rainfall. For example, potential benefits for wheat have been estimated at about 18% in temperate and tropical wheat-growing systems and 10% for rice and maize (Howden *et al.*, 2007). Research advances in agriculture and forecast modeling of crop adaptation to climate change will enhance the capacity of food producers to manage the risk, by using the new adaptation strategies; however, this is an area that needs more research effort, which should be started soon.

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DONALD SMITH received his PhD from the University of Guelph in 1984 and then held a postdoctoral fellowship at Agriculture Canada. Since 1985 he has served on the faculty of the Plant Science Department at McGill University, working largely in production and physiology of crop plants. Areas of research include nitrogen metabolism, nitrogen fixation, root-zone temperature stress and nodule development, methods for injection of metabolites into developing plants, barley production, use of plant-growth regulators, intercropping, the dynamics of inter-plant competition, plant-microbe signaling, plants and climate change and biofuel crops. He is particularly interested in physiological responses of crop plants to increasing atmospheric CO_2 levels and to climate change.

Work on nitrogen fixation has been a consistent theme, beginning with an undergraduate research project on cyanobacteria in 1974. Current work includes signaling between symbiotic partners during establishment of the legume-rhizobia symbiosis. This research activity has resulted in over 250 publications, five patents issued and three others applied for, and a spin-off company (Bios Agriculture, Inc.). Dr. Smith leads the National Sciences and Engineering Research Council-funded ($1.2 million/year) Green Crop Network on crops and climate change, including work on biofuels, and he heads the McGill Network for Innovation in Biofuels and Bioproducts.

Adapting Cropping Patterns to Climate Change

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Crops respond strongly to temperature and precipitation, and numerous studies indicate that projected changes in climate with increased atmospheric CO_2 will alter when, where and how crops are grown. Complex interactions of abiotic factors with pests, diseases, weeds and economic factors preclude an exact prescription of how climate change will affect agriculture, but there is immense value in understanding the basic aspects of possible effects. Two fundamental problems are to understand how plants may respond to the expected changes in the environment and how producers might adapt their farming practices to alleviate negative impacts and maximize the potential benefits.

Warmer temperatures usually accelerate development, resulting in earlier flowering and maturity. Warmer temperatures, however, also may allow a longer growing season if the length is otherwise delimited by early- or late-season low temperatures, including frosts. Most crops show a wide range of genetic variation for phenology, depending on their intrinsic earliness and responses to photoperiod or vernalization, so breeding likely will allow adaptive selection for crop phenologies that match changes in growing seasons. Temperature also affects potential growth and can induce acute stresses such as frost damage or heat stress. Further effects of temperature on soil processes and evapotranspiration can be expected, and although trends are less certain, climate change will also affect precipitation patterns.

Elevated CO_2 can enhance photosynthesis and reduce transpiration, resulting in increased yields and more efficient use of water. The responses are more pronounced in species possessing the C_3 mechanism than in C_4 and CAM species due to the CO_2 concentrating mechanisms of the latter two groups. Plants show numerous other responses to CO_2, including changes in phenology, leaf anatomy and dark respiration, but it is unclear whether these are direct responses to CO_2 or indirectly reflect effects of increased carbohydrate levels or decreased transpiration.

Attempts to assess potential impacts of climate change on agriculture, including options for adaptation, have largely focused on yield. However, potential changes in cropping patterns, involving both geographic distribution and temporal sequences, may require adaptive changes in research, marketing and processing. This paper describes two types of modeling that are useful in examining possible effects of climate change on cropping patterns. Ecological niche modeling, also known as bioclimatic envelope modeling, predicts the geographic distribution of a given species or population based on environmental factors assumed to influence its adaptation. Crop-simulation modeling uses quantitative descriptions of physiological processes to describe crop growth and development over time, allowing for influences of weather, soils and management. Thus, in addition to yield effects, simulations can provide valuable insights into how management, especially planting dates, and phenology might respond or be adapted to new production situations emerging from climate change.

Ecological Niche Modeling

The ecological niche of a population is its position in an ecosystem as delimited by abiotic and biotic factors. If geographic variation in these factors can be quantified and the population-specific limits defined for the factors, then the niche may be modeled and mapped. Effects of climate change on the geographic distribution of a given population are represented by remapping the niche using climate data that have been modified according to predictions from global or regional climate models.

The geographic distribution of a crop is modeled starting from data identifying locations where the crop is known to occur. This information is then linked to data on climatic, edaphic (soil), biotic or socioeconomic factors that are thought to delimit the geographic distribution of the crop. Climate data are of particular interest and are usually described through gridded (raster) surfaces. These are obtained by interpolating large sets of data from weather stations for variables such as mean monthly temperatures or total precipitation. The interpolations typically account for effects of elevation, and global sets of monthly data are available on a roughly 5-km (2.5 arc minute) grid *(e.g.*, Hijmans *et al.*, 2005).

There are numerous methods for modeling ecological niches, including environmental envelope techniques, classification tree analysis, generalized linear models, neural networks and genetic algorithms (Elith *et al.*, 2006; Heikkinen *et al.*, 2006). Methods differ in whether they consider only locations where the target organism is known to be present vs. methods that consider both presence and absence. Further differences include whether locations are assumed to be exact or to contain measurement error and whether spatial autocorrelation is considered.

The BIOCLIM method as implemented in the DIVA-GIS software package (Hijmans *et al.*, 2001) provides a useful introduction to niche modeling because of its simplicity. A set of location data is obtained, and through preliminary analyses, a set of explanatory climate variables are selected, such as total annual precipitation or mean minimum temperature of the coldest month. An envelope (multidimensional space) is defined, the dimensions of which correspond to the factors being considered. The border of the envelope corresponds to the upper and lower limits of each variable as determined from the locations where the species is known to occur. Regions outside the envelope are coded as completely unsuitable. Within the envelope, zones of increasing suitability are identified based on the portion of locations that would fall within a given range of the climate variables. The climate variables are represented through gridded surfaces, where each cell for a given variable has a unique value. In defining the envelope, the cells within the 20–80 percentile range are considered to have "excellent" suitability, cells within the 10–20 or 80–90 percentile ranges have "very good" suitability, and so on to the 100 percentile limit.

Geographic Distribution of Wheat in North America

Based on geographic and temporal patterns, three classes of wheat crops in North American are conventional spring wheats, fall-sown winter wheats and winter-sown spring wheats. Conventional spring wheats mainly occupy the coldest, northernmost regions where winter survival of winter wheats is low due to cold stress, which may involve drought effects and amount of snow cover. The northern edge of winter-wheat distribution reflects conditions where the season is too short for economic production and risks of frost injury or winter drought stress are high. Winter wheats cover a large belt extending to the Gulf Coast. Their vernalization requirement ensures that after fall establishment, they remain vegetative until favorable growth conditions return in the spring. Over-wintering also requires cold tolerance. Key climatic limits along their southern margin are whether the winters are cool enough to vernalize the crop and whether temperatures during grain filling are mild enough to ensure good yields. Winter-sown spring wheats are found in southern regions, mainly in California and Arizona where risk of frost injury is low. We emphasize that while these broad patterns hold, local circumstances including biotic stresses and options for crop rotations also can affect the choice of wheat system.

To help guide wheat research across continents, the International Maize and Wheat Improvement Center (CIMMYT) developed a formal classification of global wheat megaenvironments (MEs) (Rajaram and van Ginkel, 2001; Hodson and White, 2007). Within this system, the traditional spring-wheat environments are ME6, and the fall-sown, irrigated spring-wheat environments are ME1. A logical expectation is that global warming will result in ME1 and ME6 shifting northward. Working from a database of locations classified by ME, the various climate variables available with DIVA-GIS were examined to determine which variables best delimited the respective MEs. For ME1, which was delimited by the mean temperature and total precipitation of the coolest quarter and the mean minimum temperature of the coldest month, the modeled historical distribution agreed well with the location data (Fig. 1A), although the modeled distribution extends further eastward, suggesting a need to consider whether rainfall levels are low enough to require irrigation.

A set of climate data for the year 2100 is available for DIVA-GIS, based on the National Center for Atmospheric Research climate model CCM3 simulations (Govindaswamy *et al.*, 2003). The criteria used to delimit ME1 were applied to the grids for the future climate, thus producing a map of the projected distribution of ME1 (Fig. 1B). In the western United States, the most striking difference was that ME1 is predicted to cover a larger area of the Central Valley of California. At the same time, however, the ME1 region along the western coast of Mexico is much reduced. The map also suggests that winter-sown spring wheats could be grown along a much wider band along the US Gulf Coast, but it should be noted that the analysis does not consider possible pest and disease problems, which are more prevalent in humid regions.

A similar analysis was conducted for ME6 considering four climate variables (Fig. 2). The mean maximum temperature in the warmest month was used to exclude regions with excessive summer temperatures, and the mean temperature in the warmest quarter was intended to ensure that the growing season was warm enough for wheat. The mean temperature of the coldest quarter was used to identify regions where winters are too severe for survival of winter wheats. Finally, the total precipitation in the wettest quarter was used to test whether there was enough summer moisture for production. The most striking changes with climate change were that suitable areas largely disappeared in the continental United States and that the regions classified as excellent were displaced both northward and westward, making parts of Alberta especially suitable. It is noteworthy that the displacement of ME6 northward should correspond to an expansion in the area suitable for winter wheat, so, without further analysis, it is difficult to assess the net impact on total wheat area.

These analyses are subject to various improvements. The list of sites should be expanded both for current wheat-producing locations and for sites where wheat is not grown. A more accurate delimitation of ME1 would require consideration of access to irrigation, which likely will be reduced by climate change. Elevated CO_2 can increase canopy temperature and reduce water use, and adjustments likely are needed to reflect these effects. Suitability of soils and terrain should also be assessed since regions that are suitable climatologically may otherwise prevent production. Heikkinen *et al.* (2006) have reviewed additional issues in niche modeling under climate change.

CROP-SIMULATION MODELING

Crop-simulation models are widely used to predict impacts of climate change on agricultural production, including in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Easterling *et al.*, 2007). Their ability to integrate effects of weather, soils and crop management, and predict changes in a wide range of crop and soil parameters, makes them logical choices for investigating the potentially complex interactions among environment and crop management. Most applications of models in climate-change research have emphasized impacts on individual crops and mainly considered changes in economic yield. In regions where climatic conditions permit year-round cropping, however, changes in potential planting dates and crop durations may allow important adaptive changes in cropping patterns. The ability of simulation models to predict how yield and phenology change with planting dates make them highly suitable for examining temporal changes in crop sequences. Before illustrating a simple example for irrigated systems in Arizona, a brief description of simulation models is given.

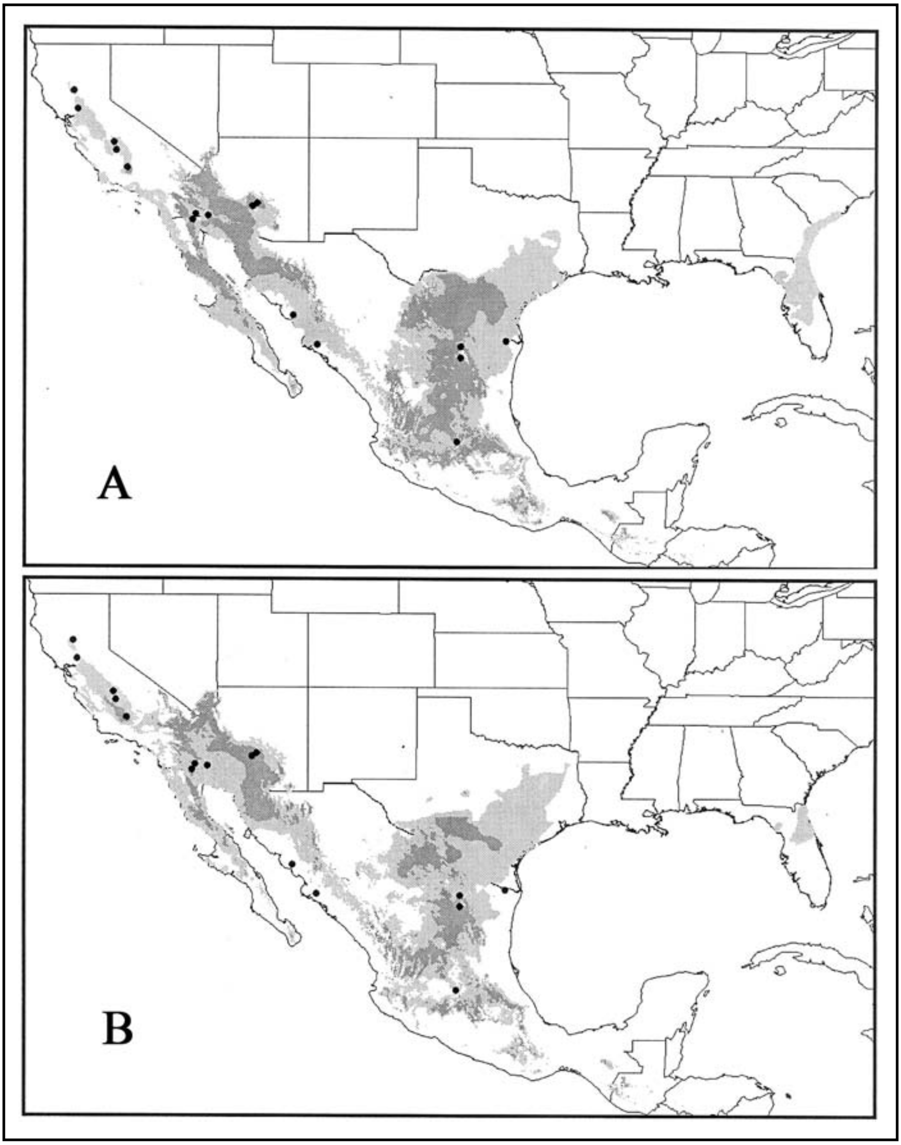

Figure 1. Distribution of wheat megaenvironment 1 (ME1) of the CIMMYT classification for winter-planted, irrigated spring types in North America as modeled with the BIOCLIM tool of DIVA-GIS (Hijmans *et al.*, 2001). Points indicate locations classified as belonging to ME1, and shaded regions indicate good to very good (light gray) or excellent (dark gray) suitability. A: Based on historical climate data. B: Based on modeled climate for 2100.

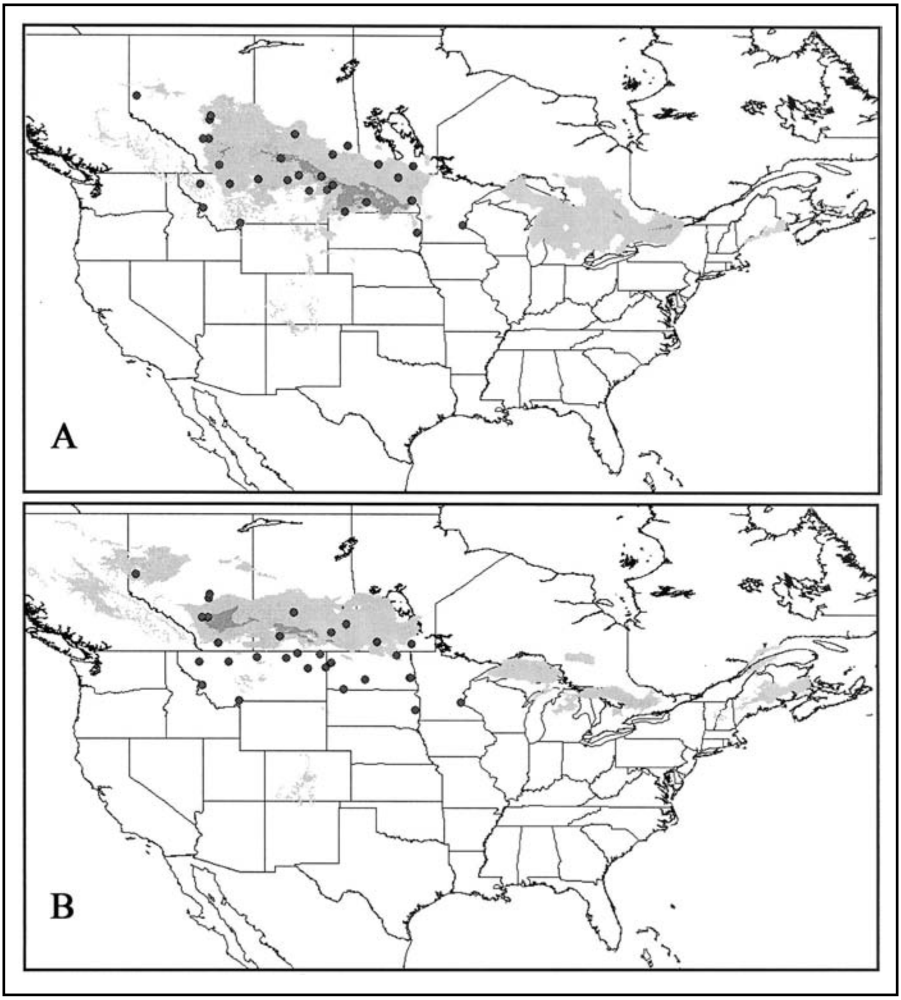

Figure 2. Distribution of wheat megaenvironment 6 (ME6) of the CIMMYT classification for traditional spring types in North America as modeled with the BIOCLIM tool of DIVA-GIS (Hijmans *et al.*, 2001). Points indicate locations classified as belonging to ME6, and shaded regions indicate good to very good (light gray) or excellent (dark gray) suitability. A: Based on historical climate data. B: Based on modeled climate for 2100.

Simulation Models

Simulation models quantify key processes of crop growth and development as influenced by weather, soils, management and the genetic attributes of the plant (at the species or cultivar level). Information on these factors is provided as inputs to the model. From soil initial conditions and planting information, the model estimates increments of growth and development, which are integrated over time, typically using hourly or daily time intervals. Growth is described as the balance of gains through photosynthesis and losses due to respiration and senescence. The rate of photosynthesis may vary with light interception, temperature, CO_2 and the water and nutrient status of the crop. Respiration may depend on temperature and the metabolic activity of the tissue, which is often related to tissue-protein concentrations. The cost of biosynthesis of tissues varies with their composition—cellulose, starch, sugars, lignins, lipids, proteins and other components—which also contributes to net respiration.

Development usually involves predicting a series of phenological stages such as seedling emergence, floral initiation, anthesis and physiological maturity. These are modeled by assuming that intrinsic developmental rates are modified by temperature, photoperiod or other factors. Often, differences in the intrinsic rates and in photoperiod response are key determinants of the ability of a model to represent genetic differences among cultivars.

Information on development guides a set of rules used to partition growth among different organs. In seed crops prior to anthesis, priority is given to leaf growth, but water or nutrient deficits may increase allocation of assimilate to roots. Post-anthesis growth gives increasing priority to fruits or seeds, often involving remobilization of assimilate and nitrogen from vegetative tissues. To simulate effects of water and nutrients, additional procedures are used to estimate levels of water and nutrients in the soil and their availability to the crop. This may involve extensive modeling of soil and atmospheric processes.

The simplest models estimate daily growth using a concept of radiation-use efficiency, while the most complex models calculate photosynthesis, transpiration and energy fluxes on sub-hourly time scales. Hay and Porter (2006) review the underlying physiology embodied in different models, and Tsuji *et al.* (1998) describe a series of related models and their applications to diverse problems, including climate-change research.

Simulating Cropping Sequences under Climate Change: Cotton, Sorghum and Wheat in Arizona

Both hot- and cool-season annual crops are grown in the irrigated, arid croplands of Arizona. For summer crops, heat stress and very high water use are potential concerns and might be exacerbated under climate change, but warmer spring or fall conditions might improve conditions for cropping outside of the period of peak summer heat. For winter crops especially, reduced frequency and severity of frost injury might allow a longer cropping season. Yield responses to planting date for three crops, cotton, sorghum and wheat, are compared to illustrate how shifts in the cropping season of one crop might affect options for the other crops. The analyses include a climate-change scenario of +1.5°C for daytime temperatures, +3.0°C for nighttime temperatures, and 580 ppm CO_2, approximating a "business as usual" scenario for 2100.

For cotton (Fig. 3), the simulations suggest that although warming will lengthen the growing season, it would result in a much more bimodal response to planting date, with planting dates from mid-March to late May producing lower yields. Elevated CO_2 largely compensates for the yield reduction. Although the highest yields are for February

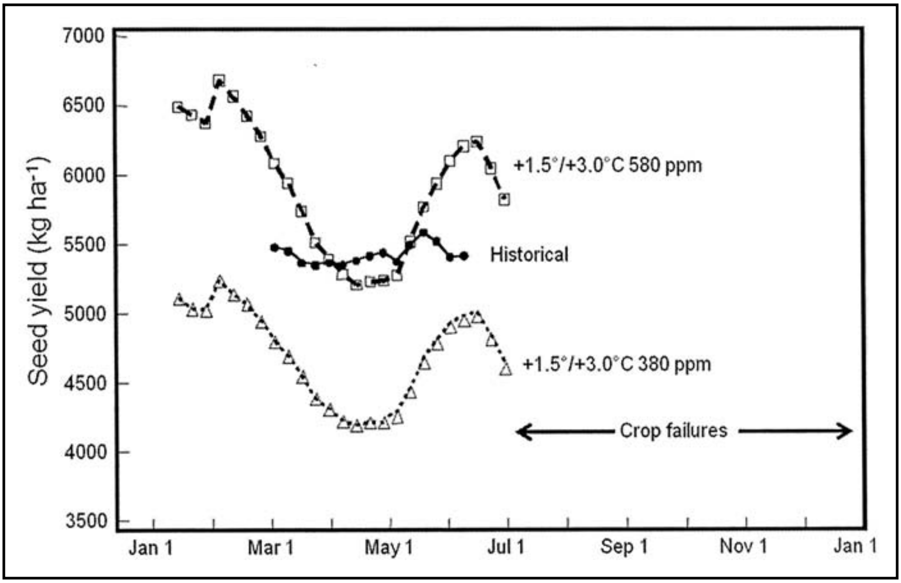

Figure 3. Response of cotton-seed yield to planting date at Maricopa, AZ, as simulated by the CSM-CROPGRO-Cotton model. Historical values are means of results from 1987 to 2008 and assume a CO_2 of 380 ppm. Planting dates with no yield correspond to crop failures due to low temperatures.

plantings, a mid-June planting offers high yield with an increased possibility of planting a winter crop. Thus, Figure 4 compares crop yields and durations for cotton, sorghum and wheat under climate-change and historical scenarios. The specific planting dates were selected allowing for flexibility in order to obtain near maximum yields while permitting a wider range of cropping options. Cotton planted in mid-June and reaching maturity in early November leaves time for a December-planted wheat. The wheat would mature by late May, potentially allowing a cotton-wheat rotation. Such rotations are widespread in northwestern India and in Pakistan (Mayee *et al.*, 2007), and a cotton-barley rotation is already used in Arizona.

Although early-planted sorghum could be grown slightly earlier, it would still overlap with both wheat and cotton, thus precluding annual rotations. The slight loss of sorghum yield with climate change reflects the low responsiveness of C_4 crops to elevated CO_2 plus a shorter growth duration. For all three crops, it is likely that fine-tuning of phenology might improve net annual economic yield of the systems.

Opportunities for Plant Biology

While the two types of modeling may seem remote from agricultural biotechnology, there are important avenues for plant biology to improve our ability to predict crop phenotypes from the interacting effects of genotypes, environmental factors and management prac-

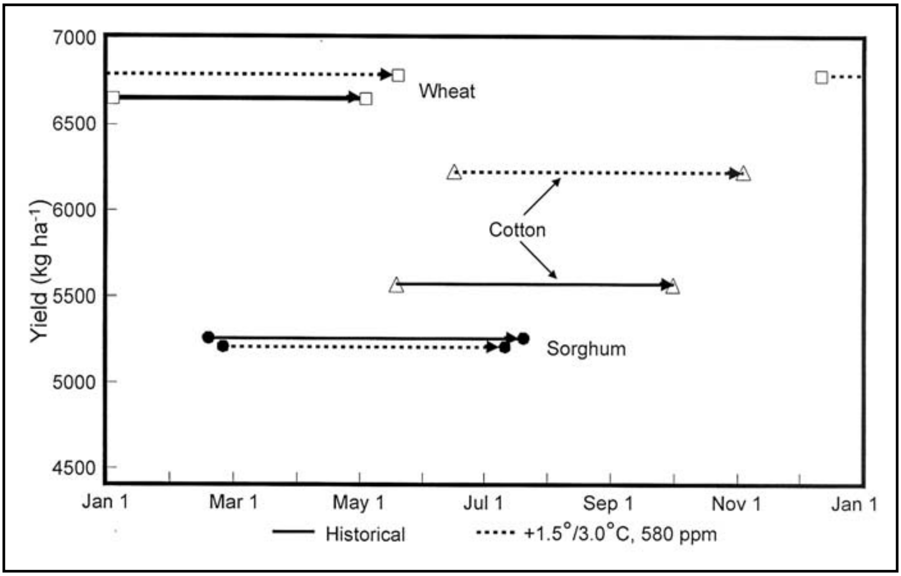

Figure 4. Relations among yields, planting dates and harvest dates for cotton, sorghum and wheat at Maricopa, AZ, simulated for historical weather data from 1987 to 2008 or a climate change scenario of an increase in daily maximum temperature of 1.5°C and an increase in minimum of 3.0°C and a CO_2 concentration of 580 ppm. For cotton and wheat, the combinations of planting dates and yields for climate change were selected considering tradeoffs between yield and options for double cropping.

tices. These include improved characterization of cultivars and refining the physiological assumptions of the models.

Simulation models typically represent cultivar differences through cultivar-specific parameters for traits like photoperiod sensitivity, earliness *per se* and representative grain size. The parameters are evaluated through an iterative process of adjusting their levels until simulations of traits such as time of anthesis and grain number per unit area adequately match values obtained in field trials. Efforts to estimate the parameters based on the genetic makeup of cultivars show promise (White *et al.*, 2008), but they have been constrained by the lack of information on loci affecting traits used as model parameters and by the scarcity of accurate data on the genetic makeup of cultivars when loci are known. Although plant biology has vastly improved our ability to identify and characterize loci, increased focus on traits relevant to ecophysiological models is needed.

A second avenue is for plant biology to improve the understanding of underlying processes, thus allowing the simulation models to describe plant responses more accurately. For example in modeling phenology, there is uncertainty over when a plant becomes sensitive to photoperiod and whether photoperiod sensitivity persists after floral initiation. Studies of temporal variation in mRNA levels of key loci involved in control of flowering should clarify how to model photoperiod responses, possibly also suggesting key diagnostic tests in field experiments. Clarification of how plants sense CO_2 levels, such as in the response of guard cells to CO_2, might indicate whether a common mechanism underlies effects of CO_2 on phenology, leaf structure and dark respiration that are not yet considered in crop-simulation models. Numerous other examples could be mentioned and, indeed, much of plant biology dealing with photosynthesis, respiration, development and plant responses to abiotic stresses is potentially of value for guiding how specific processes are modeled.

Conclusions

The potential impacts of climate change on cropping patterns are highly researchable but present significant methodological challenges. The examples for wheat regions of North America and cropping systems in Arizona demonstrate that climate-change impacts are not simply a question of increased or decreased productivity. The impacts may have dramatic effects on land use as well as cropping practices in a given region. Ecological niche modeling and crop-simulation modeling are powerful, complementary tools for examining the spatial and temporal aspects of climate-change impacts. Their successful application, however, requires effective interdisciplinary collaboration, including participation from plant biology.

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JEFFREY WHITE is a plant physiologist who emphasizes use of ecophysiological models and geospatial tools to understand how crops respond to environment. He obtained his training at Harvard College and the University of California-Berkeley. His early research on common bean, conducted at the International Center for Tropical Agriculture (CIAT) in Colombia, emphasized understanding the physiological and genetic bases of cultivar differences in yield potential, adaptation to water deficits, and responses to photoperiod and temperature. Achievements at CIAT included identifying two major loci controlling photoperiod response and demonstrating that higher yield under drought was associated with greater extraction of soil moisture, which depended on traits controlled by genes expressed in the roots.

Moving to the International Maize and Wheat Improvement Center (CIMMYT) in Mexico in 1995, he established the first GIS and crop modeling laboratory. His group revised CIMMYT's mega-environment classifications for maize and wheat research, and successfully promoted use of geospatial tools at national and regional scales such as for efforts to develop drought-tolerant maize in eastern and southern Africa. In 2003, Dr. White joined USDA-ARS in Arizona, where he works on predicting crop response to global change, continuing his work with models and geospatial tools.

He has (co)authored over sixty journal papers and supervised fifteen MSc and PhD theses.

Table of Contents

Soil and Water Management Options for Adaptation to Climate Change

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Atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gasses (GHGs) have been drastically influenced by anthropogenic activities. Humans have perturbed the global carbon (C) cycle for about 10,000 years since the dawn of settled agriculture (Ruddiman, 2003, 2005; Brook, 2009). Agricultural activities that have caused emission of GHGs from terrestrial ecosystems (biota and soil) include deforestation, biomass burning, soil tillage, and drainage of wetlands. In addition, domestication of cattle and cultivation of rice paddies, around 5,000 years ago, caused emission of methane (CH_4). Use of animal manure and plowing under of leguminous green-manure crops, widely practiced in South and East Asia for millennia, also increased emissions of nitrous oxide (N_2O). The rate and magnitude of the emission of GHGs increased drastically with the onset of the industrial revolution because of reliance on fossil-fuel combustion for energy. Yet, until the 1940s, more CO_2 was emitted from land-use conversion and agricultural activities than from fossil-fuel combustion. The data in Table 1 show that globally averaged mixing ratios reached high values in 2007 with atmospheric concentrations of 383 ppmv for CO_2, 1,789 ppbv for CH_4 and 321 ppbv for N_2O (WMO, 2006, 2008). In comparison with pre-industrial (~1750) concentrations, these values have increased by 37% for CO_2, 156% for CH_4 and 19% for N_2O (Table 1).

Table 1. Atmospheric concentrations of major greenhouse gases in 2007 (WMO, 2008).

Parameter	CO_2	CH_4	N_2O
Concentration in 2007 (ppm)	383	1,790	321
% increase since ~1750	37	156	19
Absolute increase in 2006–2007 (ppm)	1.9	6.0	0.80
% increase in 2006–2007	0.50	0.34	0.25
Mean annual absolute increase since 1997 (ppm)	2.0	2.7	0.77

Emissions from fossil-fuel combustion and cement manufacture between 1750 and 2006 are estimated at 292 to 330 Gt (Canadell *et al.*, 2007; Holdren, 2008). Projected emissions from fossil-fuel combustion between 2004 and 2030 are estimated at an additional 200 Gt C (Holdren, 2008). In comparison, emissions from land-use change (*e.g.* deforestation, soil cultivation, drainage of peatland) between 1850 and 2006 are estimated at 158 Gt C. Ruddiman (2003, 2005) estimated that C emission from terrestrial ecosystems, because of agricultural activities from ~10,000 years ago to 1850, may be 320 Gt. If Ruddiman's estimates are nearly correct, terrestrial ecosystems may have contributed as much as 478 Gt of C since the dawn of settled agriculture.

Because of the direct link between atmospheric concentration of GHGs and abrupt climate change (ACC) (IPCC, 2007a), there is a strong interest in identifying strategies for mitigation of, or adaptation to, climate change. The ACC refers to rapid change in temperature (>0.1°C/decade) such that ecosystems cannot adjust, and biomes shift poleward. Mitigation of global warming and ACC will involve taking action to reduce GHG emissions and to enhance sinks aimed at reducing the extent of global warming (IPCC, 2007b). In comparison, adaptation to global warming will consist of initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected ACC effects (IPCC, 2007b). This manuscript reviews potential and challenges related to soil- and water-management options for adaptation to ACC.

World Soils and the Global Carbon Cycle

There are five principal global C pools (Fig. 1). The largest pool is lithospheric and the vast amount of C stored as sediment carbonates and kerogens is mostly inactive (out of circulation) and interacts with the atmospheric pool mainly through volcanic eruptions. The second-largest pool is oceanic, estimated at 37,400 Gt of inorganic C (of which 670 Gt are in the surface layer and 36,730 Gt are in the deep layer) and ~1,000 Gt of organic C. The third-largest pool of fossil fuel is estimated at 4,130 Gt, comprising coal, oil, gas and peat. The fossil-fuel pool is being mined and combusted at the rate of 8.0 Gt C/year. The fourth-largest pool, soil C, is estimated at 2,500 Gt to a depth of 1 m and >4000 Gt to 2 m (Batjes, 1996). The soil-C pool is being depleted at a rate of 0.1 Gt C/year or more. The fifth-largest pool, atmospheric, presently contains 780 Gt C and is increasing at >4 Gt C/year. The sixth-largest pool is the biotic pool, comprising 620 Gt of terrestrial and 102 Gt of aquatic components. The atmospheric, biotic and soil pools are closely interlinked (Fig. 1).

The biotic pool photosynthesizes ~120 Gt C/year. Of this, 59 Gt C/year is returned to the atmosphere through decomposition of biomass (plant respiration) and 58 Gt C/year through soil respiration. The oceanic pool is absorbing 2.3 Gt C/year and its sink capacity may increase with progressive increases in its partial pressure along with atmospheric concentration of CO_2. The atmospheric pool is absorbing ~4 Gt C/year. Canadell *et al.* (2007) computed the relative efficiency of natural sinks by evaluating the airborne fractions (AFs), the ratio of atmospheric CO_2 increase in a given year to that year's total emission. The data in Table 2 show that AF was 49% in the 1980s, 40% in the 1990s and 44% in the 2000s. It seems that the natural sink capacity in 2008 is lower (by ~2%) than that in the 1990s, probably because of soil degradation or decline in quality of soil and water resources. The global-C budget (Table 2) shows that natural sinks (soil, biota, ocean) absorb ~56% of the anthropogenic emissions. The strategy is to enhance sink capacity of soil and biota through judicious and sustainable management of natural resources, and targeted interventions.

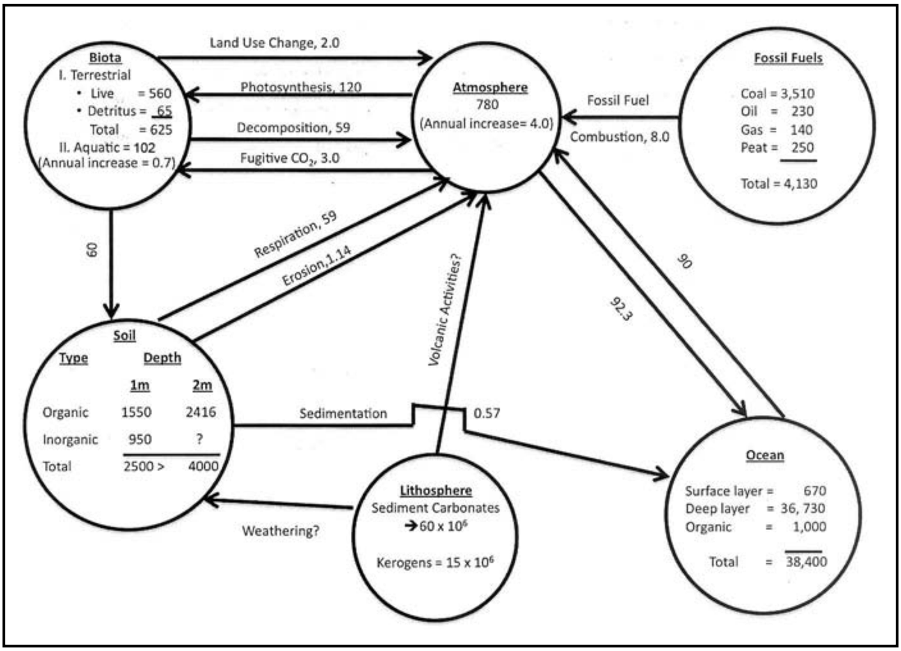

Figure 1. Principle global carbon pools and fluxes among them (Lal, 2004b; Houghton, 2001; Falkowski *et al.*, 2000; Canadell *et al.*, 2007; Koonin, 2008). All pools are in Gt and fluxes are in Gt/year.

TABLE 2. CONTEMPORARY GLOBAL CARBON BUDGET (IPCC, 2007A; HOUGHTON, 2001; FALKOWSKI ET AL., 2000; CANADELL ET AL., 2007).

Parameter	**Flux (Gt/year)**		
	1980s	**1990s**	**2000s**
Sources			
Fossil-fuel combustion	5.4	6.4	7.5
Land-use conversion	1.4	1.6	1.6
Total	6.8	8.0	9.1
Sinks			
Atmosphere	3.3	3.2	4.0
Ocean	1.8	2.2	2.3
Land	0.3	1.0	0.9
Total	5.4	6.4	7.2
Unknown land sink	1.4	1.4	1.9
Natural sinks (% of total source)	51	59	56

TABLE 3. ESTIMATES OF CHANGES IN AREA FOR DIFFERENT VEGETATION TYPES BETWEEN 1700 AND 1992 (RAMANKUTTY AND FOLEY, 1999).

Vegetation	Decrease in total area ($\times 10^6$ ha)
Forest and woodland	1,135
Savanna, grassland, and steppe	669
Tundra and polar deserts	26
Total	2,025

LAND-USE CONVERSION, SOIL DEGRADATION AND DESERTIFICATION

The historic loss from terrestrial and aquatic C pools (wetlands) is estimated at 478 Gt C. These emissions are mainly from the biotic- (trees and biomass) and soil-C pools. Increases in population caused drastic alterations in vegetation cover between 1700 and 2000 through conversion of 2,025 million ha (Mha) of natural ecosystems (Table 3) and their conversion to an additional global cropland area by 1,135 Mha (Table 4), with attendant increases in global cropland area from merely 235 Mha in 1700 to 1,520 Mha by 2005 (Table 5). These alterations in land use resulted in expansion of areas under cropland, grazed pastures, forest plantations and urbanization (Table 6) with corresponding decline in areas under natural ecosystems (Tables 3, 4). Indiscriminate deforestation, land misuse, soil mismanagement and widespread use of extractive farming practices caused severe degradation of soil resources. Estimates of soil degradation—preliminary and tentative as these may be—are alarming (Table 7). Areas affected by a range of soil-degradation processes are estimated at a total of 1,965 Mha (Oldeman, 1994). In contrast, areas prone to land degradation (3,506 Mha, Bai *et al.*, 2008) and desertification (3,592 Mha, UNEP, 1991) are 1.8-fold higher (Table 7).

The extent and severity of soil degradation and desertification imply:

- loss of reserves of soil organic matter (SOM),
- depletion of plant nutrients,
- decline in cation-exchange capacity (CEC) because of reduction in soil colloids (clay and humus fractions) caused by accelerated erosion,
- change in soil reaction caused by acidification or alkalization,
- elemental imbalance caused by deficiency of some (N, P, K) and toxicity of others (Al, Fe, Mn),
- adverse shift in soil fauna and flora (build up of soil-borne pathogens),
- reduction in plant-available water retention capacity in soil, leading to increased intensity and duration of drought,
- loss of soil structure and tilth exacerbating problems of crusting, compaction, and anaerobiosis, and

- increase in emission of GHGs due to high rates of decomposition of biomass caused by changes in soil temperature and moisture regimes, and increases in methanogenesis and denitrification.

These degradative trends are vastly accentuated by observed and predicted ACC. Increases in air and soil temperatures will increase risks of soil degradation because of increases in:

- the rate of mineralization of SOM,
- soil erodibility and climatic erosivity,
- losses of water by surface runoff and evaporation, and
- losses of plant nutrients by leaching, erosion and volatilization.

The ACC may also reduce efficiency of use of inputs (*e.g.* fertilizer, nutrients).

Table 4. Estimates of conversion of forest vegetation to cropland between 1700 and 1992 (Ramankutty and Foley, 1999).

Forest	**Land area converted to agriculture (x10^6 ha)**
Forest and woodland	422
Temperate forests	451
Boreal forests	40
Evergreen deciduous forest and woodland	222
Total	1,135

Table 5. Estimates of increases in area under cropland and pastures between 1700 and 1980 (FAO, 2008; Richards, 1990).

Year	**Cropland**	**Grazing land**	**Pasture**
		(x10^6 ha)	
1700	265	6,860	–
1850	537	6,837	–
1920	913	6,748	–
1950	1,170	6,780	–
1980	1,346	6,788	3,244
1990	1,396	–	3,368
2005	1,402	–	3,442

TABLE 6. LAND USE FOR THE WORLD AND SOME COUNTRIES IN 2005 (FAO, 2008).

Land use	Area (x10^6 ha)				
	World	U.S.	China	India	Canada
Total land area	12,980	916	933	297	909
Arable land	1,402	176	137	160	46
Pastures	3,442	234	400	11	15
Forest land	3,952	303	197	68	310
Woodland	1,342	–	88	4	92
Productive plantations	0.34	0	0	0.10	0
Protected plantations	1.53	0	0	0.22	0
Urban land	351	19	24	21	13

TABLE 7. ESTIMATES OF DEGRADED AND DESERTIFIED LANDS.

Type	Area (x10^6 ha)	Methodology	Reference
Soil degradation	1,965	Glasod	Oldeman (1994)
Land desertification	3,592	Dregne	UNEP (1991)
Soil desertification	1,137	Glasod	Oldeman & Van Lynden (1998)
Vulnerability to desertification	4,324	Land capability	Eswaran *et al.* (2001)
Land degradation	3,506	NPP loss	Bai *et al.* (2008)

TABLE 8. WORLD TOTAL FERTILIZER CONSUMPTION (TILMAN ET AL., 2001; IFDC, 2004; PONTING, 2007).

Year	N	P	K	Total
	(x10^6 Mg/year)			
1900	0.41	0	0	0.41
1950	9	0	0	9
1960	12	11	9	32
1970	32	21	16	79
1980	61	32	24	117
1990	77	36	5	138
2000	81	33	22	136
2002	85	34	23	142
2020	135	–	–	–
2050	236	–	–	–

AGRICULTURAL INTENSIFICATION AND C-BASED INPUT

Crop yields increased by a factor of 3 to 5 during the second half of the 20th century despite degradation of soil, desertification of land, and depletion/pollution of water resources. This quantum jump in crop yields and the overall increase in agronomic production was brought about by agricultural intensification through adoption of varieties that were responsive to inputs. For example, world fertilizer use increased from $<0.5\times10^6$ Mg/year in 1900 to 142×10^6 Mg/year in 2002, *i.e.* by a factor of 342 (Table 8). The use of nitrogenous fertilizer is expected to increase from 85×10^6 Mg/year in 2002 to 135×10^6 Mg/year in 2020 and to 236×10^6 in 2050 (Table 8). Similar to fertilizer use, the area under irrigation has increased by a factor of 20 since 1800 and of 6.7 since 1900 (Table 9). The irrigated land area increased from 16 Mha in 1800 and 41 Mha in 1900 to 277 Mha in 2003 (Table 9). Less than 20% of the irrigated cropland area produces more than 40% of the agronomic output. However, future increases in irrigation, most likely to occur in Africa and South America, will exacerbate competition for water resources from rapidly increasing demands from non-agricultural (*e.g.* urban, industrial) uses (Table 10). The non-agricultural use of water increased drastically between 1900 and 2000, from 20×10^9 m^3/year to 440×10^9 m^3/year (*i.e.* by a factor of 22) for urban land use and from 30×10^9 m^3/year to 1900×10^9 m^3/year (*i.e.* by a factor of 63) for industrial uses (Table 10). Consequently, agricultural use of water (as a % of total consumption) decreased from 81% in 1900 to 57% in 2000, and will continue to decrease during the 21st century

Increases in population and concomitant demands on soil and water resources drastically increased productivity and human exploitation of natural resources, often with adverse impacts on quality of soil, vegetation, water and air (Table 11). Demands for natural resources will increase even more drastically during the 21st century because of two factors: (i) increased need for food production, which may have to be doubled by 2050, and (ii) ACC which will further jeopardize the natural resources that are already under great stress (Table 11). Therefore, adaptation to climate change is essential for human survival and wellbeing.

TABLE 9. GLOBAL IRRIGATION (PONTING, 2007; FAO, 2008).

Year	Irrigated land area ($\times10^6$ ha)
1800	14
1900	41
1950	120
1960	145
1970	169
1975	189
1980	210
1990	244
2000	275
2003	277

TABLE 10. COMPETITION FOR WATER (KONDRATYEV ET AL., 2003; GLEICK, 2003A, B).

Year	Water use (x10^9 m^2/year)				
	Total	Urban	Industrial	Agricultural	
				Net	% of total
1900	430	20	30	350	81
1940	870	40	120	660	76
1950	1,190	60	190	860	72
1960	1,990	80	310	1,510	76
1970	2,630	120	510	1,930	73
1975	3,080	150	630	2,100	68
1985	3,970	250	1,100	2,400	61
1995	4,750	320	1,560	2,760	58
2000	6,000	440	1,900	3,400	57

TABLE 11. INCREASED PRODUCTION AND CONSUMPTION OF NATURAL RESOURCES, 1900–2000 (PONTING, 2007).

Parameter	Increase factor
Population	3.8
Urban population	12.8
Industrial output	35
Energy use	12.5
Oil production	300
Water use	9
Irrigated area	6.8
Fertilizer use	342
Fish catch	65
Organic chemicals	1,000
Car ownership	7,750

Adaptation to Abrupt Climate Change

There are two strategies of addressing the issue of ACC: mitigation and adaptation (Fig. 2). Mitigation implies either reducing emissions (by enhancing energy-production efficiency, and identifying low-C or no-C fuel sources) or sequestering emissions in long-lived pools (*e.g.* soil, biotic). Adaptation implies changing lifestyle, and using technologies for management of resources in a manner that minimizes the adverse effects of ACC on soil and water resources. A wide range of soil- and water-management practices can be adopted to sequester atmospheric CO_2 in terrestrial ecosystems. The technical potential of C sequestration in terrestrial ecosystems is estimated at 5.7 to 10.1 Gt C/year (Table 12). The estimated economic (3 to 6 Gt C/year) and realizable (2 to 3 Gt C/year) potentials can be accomplished through adoption of innovative methods of soil and water management, along with other strategies.

Changing lifestyle is an important consideration in adaptation to ACC. This will involve creating awareness among the public and, especially, policymakers about the importance of reducing the C-footprint of modern civilization including food production, processing and transport, and dietary preferences. In this regard, the importance of heating and cooling, lighting, water use, and transportation cannot be over-emphasized.

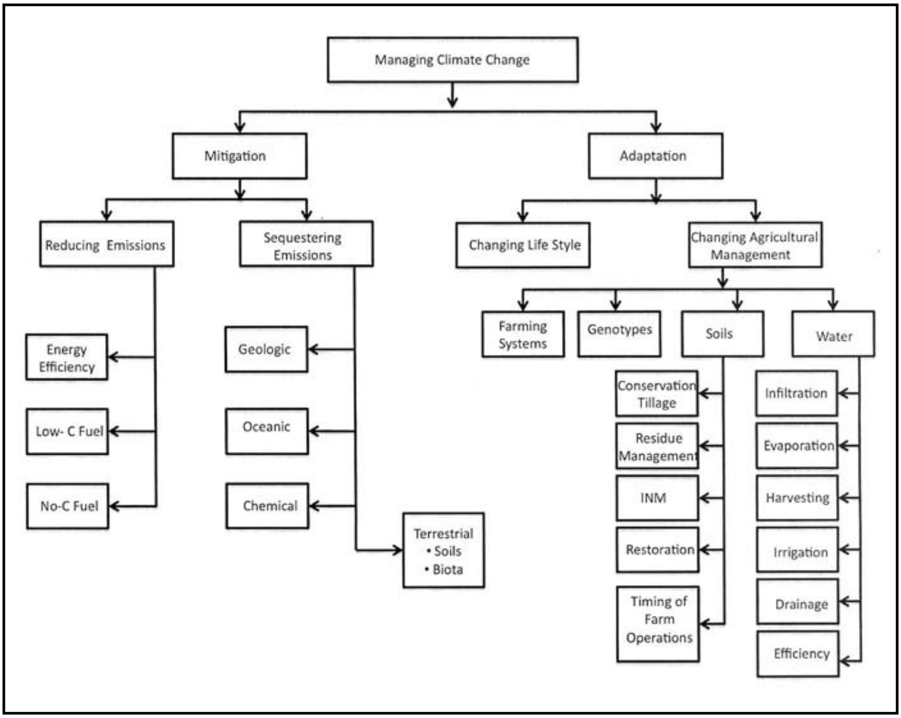

Figure 2. Strategies for mitigation and adaptation to climate change (INM=integrated nutrient management).

TABLE 12. TECHNICAL CARBON SEQUESTRATION POTENTIAL IN VARIOUS BIOMES (USDOE, 1999).

Biome	**Technical potential (Gt C/year)**
Agricultural soils	0.85–0.90
Biomass croplands	0.5–0.8
Grassland	0.5
Rangeland	1.2
Forests	1–3
Urban forests and grasslands	?
Deserts and degraded lands	0.8–1.3
Terrestrial sediments	0.7–1.7
Boreal peatlands and other wetlands	0.1–0.7

In terms of agricultural systems, there exists a wide range of strategic options. These options are different for mitigation (Fig. 3) versus adaptation to ACC (Fig. 4). Agricultural strategies for mitigation can be categorized as follows:

- reducing emissions,
- sequestering emissions,
- avoiding emissions, and
- minimizing emissions.

The overall goal is to minimize net emission from agricultural systems by efficient management of the biomass-C pool (and fluxes) and of inputs involving high hidden-C costs (*e.g.* fertilizers, pesticides, tillage). Anthropogenic emissions of CO_2 can be sequestered by increasing: (i) SOM pool, (ii) carbonate pool, and (iii) burial of unusable biomass under anaerobic conditions. Restoration of degraded and desertified soils is an important mitigation strategy because of its large technical potential for sequestering 1–2 Pg C/year. Important among several options of avoiding emissions are: (i) using biofuels, (ii) controlling erosion, (iii) intensifying agricultural production and using land-saving technologies, (iv) controlling and managing fire, and (v) managing grazing lands and stocking rate. Managing emission of other GHGs (CH_4, N_2O) is also important because of their high global-warming potential (GWP[1]) (21 for CH_4, 310 for N_2O). There are several techniques for reducing emission of CH_4 from rice paddies (*e.g.* aerobic rice, midseason drainage, no-till and direct seeding, GM rice varieties). Restoring peatlands (by restoring drainage), and managing livestock are also important to CH_4 reduction. Efficient use of nitrogenous fertilizers is essential to reducing N_2O emission, including the use of slow-release formulations and nano-enhanced materials with zeolites.

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[1] GWP for CO_2 is 1

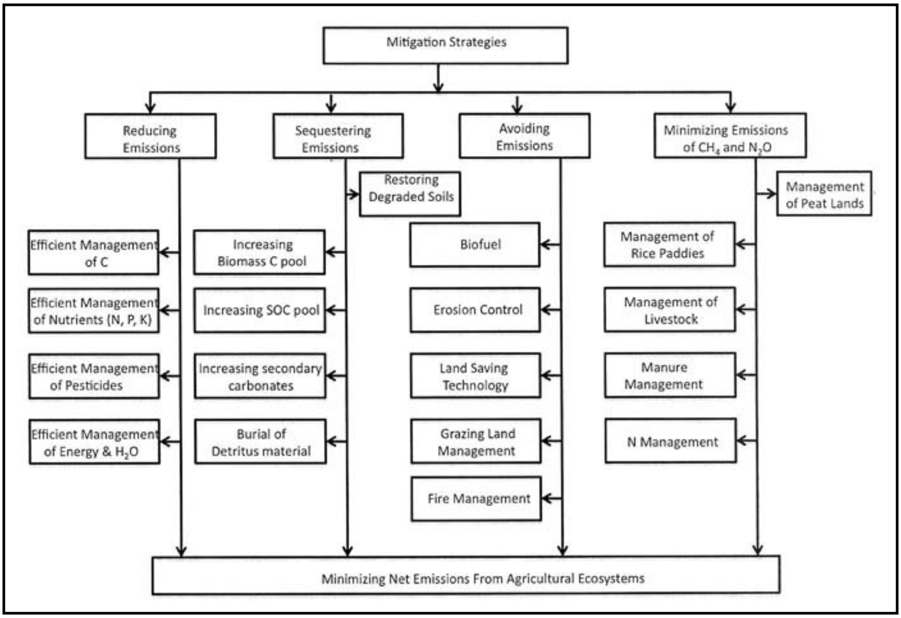

Figure 3. Agricultural strategies for mitigation of abrupt climate change (SOC=soil organic carbon)

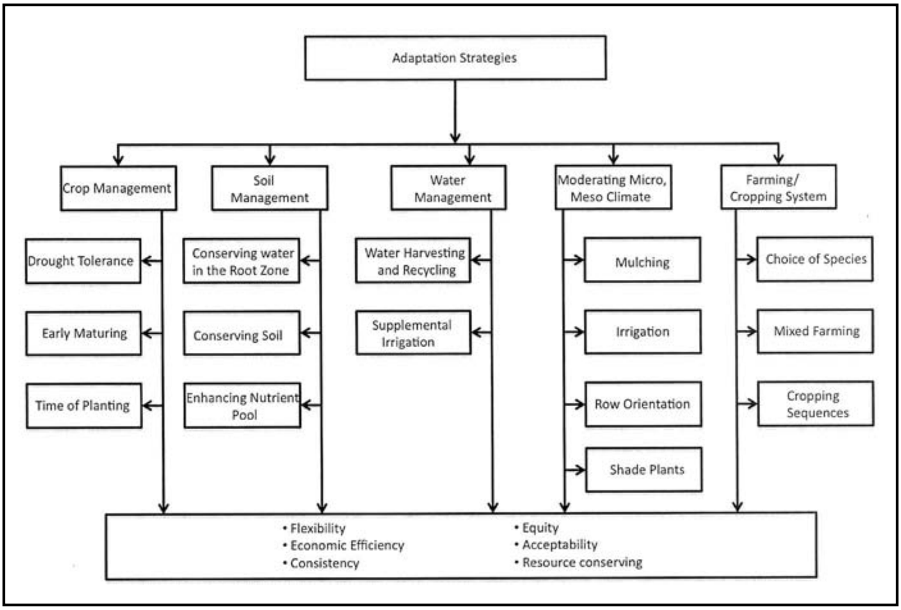

Figure 4. Agricultural strategies for adaptation to abrupt climate change.

AGRICULTURAL ADAPTATION

Important among several options for agricultural adaptation are (see also Fig. 4):

- choosing crop-management techniques including drought-tolerant (avoiding) and early-maturing varieties adopted in conjunction with adjustment in time of planting,
- converting to farming/cropping systems that reduce risks and produce minimum assured returns in bad years rather than maximum production in good years, with focus on choice of appropriate species and diversification (mixed farming),
- moderating micro- (soil) and meso-climates (canopy) to buffer against adverse impact of extreme events through mulch farming, using supplemental irrigation, row orientation, using shade-tolerant plants, *etc.*, and
- using appropriate fertilizers and soil amendments to minimize nutrient deficiencies at critical phenological stages.

Sustainable management of soil and water resources is among extremely important adaptation strategies. The goal of soil management is to conserve water, soil and nutrients in the root zone and minimize their losses from the ecosystem. The goal of water management is to conserve, harvest and recycle water while minimizing losses by runoff, evaporation, seepage and uptake by weeds.

SOIL MANAGEMENT FOR ADAPTATION TO CLIMATE CHANGE

Sustainable management of soil involves creating a positive C budget, a balanced nutrient/elemental budget, diverse soil faunal and floral activities including those of earthworms and microorganisms, and creating a favorable soil reaction (pH). Techniques to create a positive C budget are those that increase gains more than losses. Gain of C by soil ecosystems is mainly through input of biomass in the form of crop residues (above and below ground), compost, manure, mulch, cover crops, and alluvial or aeolian deposition. There may also be input of inorganic C as lime, and formation of secondary carbonates. Soil- and crop-management practices that increase the soil-C pool are outlined in Table 13. Important among nutrient-management options are slow-release formulations of fertilizer, and use of zeolites (Oren and Kaya, 2006). Biofertilization via rhizobia-legume symbioses (Lugtenberg *et al.*, 2002) is an important innovation. Increasing nitrogen fixation in legumes (Jones *et al.*, 2007) and even in non-leguminous plants (Cheng et al., 2005) can enhance N-use efficiency. The importance of root systems and especially of root exudates in improving soil structure and rhizospheric processes cannot be over-emphasized (Uren, 2000; Bertin *et al.*, 2003). Managing soils to make them disease-suppressive is an important innovation (Benitez *et al.*, 2007; Borneman and Becker, 2007, Gross *et al.*, 2007). Similar to N, there are several options for microbial enhancement of P uptake through inoculating with P-enhancing microorganisms (Legett *et al.*, 2001; Jakobsen *et al.*, 2005). There are also innovative remote-sensing technologies for improving nutrient use efficiency, such as those based on the Normalized Difference Vegetative Index (Raun *et al.*, 2001).

ADAPTATION STRATEGIES FOR WATER MANAGEMENT

There are two strategies of soil-water management: (i) conserving water in the root zone, and (ii) supplemental irrigation through surface-water management by water harvesting and recycling. Improving soil structure is essential to conserving water in the root zone and enhancing its use efficiency (Rockström *et al.*, 2007). Improvement of soil structure by application of nano-enhanced materials (*e.g.* zeolites) (Bhattacharyya *et al.*, 2006; Pal *et al.*, 2006) can enhance water-infiltration rate and decrease losses by surface runoff. Use in conjunction with crop residue or synthetic mulch (*e.g.* plastic) can minimize losses by evaporation. Growing crops in association with shrubs (*e.g. Piliostigma reticulatum* and *Guiera Senegalensis*) may enhance water use and nutrient recycling (Caldwell *et al.*, 1998; Dossa, 2007; Kizito *et al.*, 2007, 2009).

On-farm water management and supplementary irrigation are necessary to avoid drought. Micro-irrigation, especially sub-surface drip irrigation, is a modern innovation to enhance water-use efficiency (Visvanathan *et al.*, 2002; Aujla *et al.*, 2005; Molden, 2007).

POTENTIAL OF LAND RESOURCES TO ADAPT TO CLIMATE CHANGE

A wide range of recommended management practices, such as those listed in Table 13 and discussed in the previous section, has application on large areas under agricultural (Table 14) and forestry (Table 15) land uses. There also exists vast scope for expanding agriculture, especially in sub-Saharan Africa and South and Central America (Table 16). Although agricultural expansion must be undertaken only as a last resort, adoption of land-saving technologies on existing agricultural and forestry lands are important for both mitigation of and adaptation to ACC. For example, the technical potential of C sequestration is about 1 Gt/year in agricultural soils, 1 to 2 Gt/year through restoration

TABLE 13. RECOMMENDED SOIL-MANAGEMENT PRACTICES FOR ADAPTATION TO CLIMATE CHANGE THROUGH C SEQUESTRATION.

Objective	Practice	Potential (Pg C/year)
Crop-residue management	No-till, cover cropping, mulching	0.4–1.2 (Lal, 2004)
Nutrient management	Using compost, manure, balanced use of fertilizers, precision farming, nitrogen fixation, zeolites, mycorrhizae, elemental recycling, biofertilization	1 (Pacala & Socolow, 2006)
Terrain management	Strip cropping, contour hedgerow farming, contour buffers	0.85–0.9 (DOE, 1994)
Soil restoration	Afforestation, reforestation, conversion to perennial land use, agroforestry, transgenic plants	0.9–1.9 (Lal, 2001)

of degraded soils, and an additional 1 Gt/year through afforestration and establishment of biofuel plantations (Pacala and Socolow, 2004). The standing biomass is a large reservoir of C (Table 15), and management of terrestrial biomass C is important to managing atmospheric concentration of CO_2.

Table 14. Agricultural land use, 1961–2001 (IPCC, 2007b).

Land	Area (Mha)					Change	
	1961–70	1971–80	1981–90	1991–00	2001–02	(%)	(Mha)
World							
Arable land	1,297	1,331	1,376	1,393	1,405	+8	107
Permanent	82	92	104	123	130	+59	49
Permanent pasture	3,182	3,261	3,353	3,469	3,488	+10	306
Developed countries							
Arable land	648	649	352	633	613	–5	–35
Permanent	23	24	24	24	24	+4	1
Permanent pasture	1,209	1,210	1,201	1,209	1,202	–1	–7
Developing countries							
Arable land	650	682	724	760	792	+22	142
Permanent	59	68	80	99	106	+81	48
Permanent pasture	1,973	2,051	2,152	2,260	2,286	+16	313

Table 15. Regional and global area under forestland use (recalculated from IPCC, 2007b).

	Area (Mha)			C pool in live biomass (Pg C)		
	1990	2000	2005	1990	2000	2005
Africa	690	661	635	65.8	622	60.8
Asia	570	566	572	41.1	35.6	32.6
Europe	985	994	1,001	42.0	43.1	43.9
North & Central America	710	708	706	41.0	41.9	42.4
Oceania	208	207	206	11.6	11.4	11.4
South America	900	867	832	97.7	94.2	91.5
World	4,618	4,241	3,952	299	288	283

Co-Benefits of Soil- and Water-Management Options

Important global 21st-century issues include food insecurity affecting almost a billion people (Brown, 2004; Borlaug, 2007), urgency to intensify agricultural production on existing lands by raising crop yields per unit area and minimizing additional deforestation (Clay, 2004; FAO, 2004, 2005), scarcity of water resources and the need to increase and improve irrigation (Field 1990; Johnson *et al.*, 2001; Kondratyev *et al.*, 2003; Postel, 1999), and off-set fossil-fuel emissions in soils and terrestrial ecosystems for mitigating

TABLE 16. AVAILABILITY POTENTIAL OF RAINFED ARABLE LAND (READ, 2008).

Region	Potential land area (Gha)	Presently used (%)	Available land area (Gha)
Sub-Saharan Africa	1.05	15	0.893
North Africa and Near East	0.04	100	0.0
North Asia Urals Eastwards	0.28	64	0.101
Asia and Pacific	0.74	64	0.266
South and Central America	0.98	15	0.833
North America	0.43	54	0.158
Europe	0.32	63	0.118
World	3.82	38	2.38*

*1.99 Gha in tropical and 0.38 Gha in temperate regions.

ACC (Lal, 1999, 2001, 2004a, b, c; Marland *et al.*, 2001). Carbon sequestration in soils has potential to mitigate as well as adapt to ACC (Pacala and Socolow, 2004). The strategy is to create a positive C budget in soils and ecosystems through mulching with residues along with no-till farming and integrated nutrient management (West and Post, 2002; Lal, 2004a, c), and biochar application (Lehmann *et al.*, 2006). Soil-C sequestration has numerous ancillary benefits through improvement in soil quality and other ecosystem services. Restoration of degraded soils, through increases in SOC pools, improves agronomic production (Lal, 2006a) which advances food security (2006b) and improves human nutrition (Lal, 2009). Increasing the SOC pool is also important to enhancing efficacy of limited resources of N and P (Smil, 1990). There are also benefits to water quality from control of non-point source pollution. Important progress is also being made in measurement and monitoring of SOC concentration using field techniques (Ebinger *et al.*, 2003), remote-sensing devices (Shephard and Walsh, 2002) and other non-invasive and *in-situ* devices (Wielopolski, 2006; Wielopolski *et al.*, 2000).

CONCLUSIONS

Rapidly increasing atmospheric abundance of CO_2 and other GHGs leading to an increase in mean global temperature of 1 to 4°C by the end of the 21st century necessitates identification and use of relevant adaptation strategies. Depending on land use and management, sustainable agricultural ecosystems can be an important part of the solution to ACC and other environmental issues. While adjusting to time-of-farm operations and identification of appropriate species and rotation cycles, important soil- and water-management options must be carefully assessed. Sustainable soil-management options include conservation tillage with residue management, integrated nutrient management, and restoration of degraded soils. Water-management options include those that conserve water in the root zone and buffer crops against drought stress and other extreme events. These adaptation strategies are especially important to resource-poor and small landholders of the tropics. The goal of the adaptation strategies is to stabilize agronomic production against the adverse impact of biotic and abiotic stresses projected to be exacerbated by ACC.

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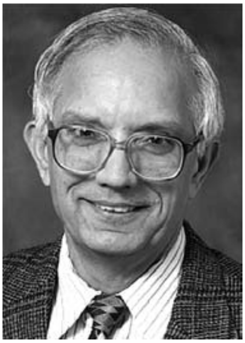

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He has (co)authored over 1,350 research publications and has (co)edited forty-three books and written thirteen.

Other Approaches to Adaptation

PANEL DISCUSSION AND Q&A

MODERATOR: ANGELA BEDARD-HAUGHN
University of Saskatchewan
Saskatoon, Saskatchewan

PANELISTS:
JEFF SCHOENAU, DAN PENNOCK, STUART SMYTH
University of Saskatchewan
Saskatoon, Saskatchewan

Jeffrey Schoenau: As a scientist and a farmer I was impressed with the information and the insight provided by the three speakers. One of the things that I found interesting on crop adaptation to climate change relates to semi-arid systems unable to support cropping in the future. That's where I farm, in the Palliser Triangle, and I guess this thought has come up before. It certainly came up in the 1930s and came up in the '80s again. But, interestingly, out in the farms you don't hear a lot of this anymore and part of the reason is because of reduced tillage and improvements in water conservation and soil conservation. Compared to 30 years ago, things are a lot better. Although that's a success story here in the prairies, I believe that there is opportunity for further water conservation in anticipation of drier conditions down the road. So, I put that forward as a challenge, that there is opportunity for further improvement.

The other thing that made me think was the talk about adaptation. You know, plants are tough. Some do well under adverse conditions. Some weeds, for example. One that I battle every year, kochia, is able to develop resistance to a wide variety of herbicides. It likes it hot. It likes it cold. It's always there. What makes it tough? Can we capitalize on some of the genetics of those kinds of plants and bring those characteristics into our cropping systems?

Talking of cropping systems, Don made me feel good because there is lots of potential for improvement. With winter crops, we can take advantage of the early spring moisture from snow melt and avoid the terminal July drought that tends to get us in the southern prairies. Early seeding of spring crops, timely planting, was brought up by a couple of speakers. If you farm 1,600 acres like I do that's a great thing, but some farms now are 16,000 acres such that timeliness can be a real challenge. That's something that's being addressed from the equipment side, but greater efficiency oftentimes means a bigger operation, for better or for worse.

The modeling was interesting *vis-à-vis* spring wheat moving north, and, as we look at changes in cropping patterns, I believe that new crops and new cropping systems will be adopted to fill niches left behind. Jeff brought up double cropping, and maybe that's something that we should start to think about here in the southern prairies. Winter peas that are harvested early in July could be followed by a short-season cereal harvested in October. This may seem farfetched and certainly it would take water to do it. Farmers would spend a lot more time in the field and would have to make better use of precipitation during the growing season, and water from snowmelt, to capture that late-season photosynthetic potential. Also important, covered by Jeff, are cropping systems, rotations, and options like planting time and row spacing. We need that kind of agronomy and extension of that information to growers so that they have a sound basis for making their decisions.

Dr. Lal built a strong case for the importance of soil and I agree with that. Organic matter does so many wonderful things for the soil itself and, of course, is an important reservoir of, and sink for, carbon. He pointed out the importance of efficiency, which is key in economics. It's key in mitigating and adapting to climate change. I tell my students in my soil fertility and fertilizer class, with regard to fertilizer nutrients: use them, don't lose them. Replace what you remove; that's very important. And when it comes to recycling efficiency, some of the research that I'm involved with gets to the whole biofuel question, *i.e.* recycling those nutrients and that carbon in byproducts like glycerol, like stillage, and manure from cattle that are fed distillers grains. Those are ways to get those nutrients and carbon back into the system. A lot of fertilizer will be needed to achieve the yields that we will need down the road and we must find ways to be more efficient. One of the ways is putting back in what you take out by adding to the land products that might be considered waste, but actually when managed properly are an important resource.

Bedard-Haughn: Dr. Pennock would you like to respond?

Dan Pennock: I echo what Jeffrey said: it's heartening to realize the range of options open to us to deal with climate change. Sometimes it's presented as almost a hopeless case, but we heard about genetic improvement, variety improvement, cropping practices and soil changes. All the adaptations that we've talked about will be evaluated for yield or biomass response but also increasingly in terms of associated greenhouse-gas costs. Nations now have to do accounting for their greenhouse-gas balances and, increasingly, sectors and individual farmers will do so. The northward expansion of spring wheat is a good example, to which Don alluded. If you move out of the grassland soils in the prairies you are moving into an area that is forested, and there is a tremendous carbon loss associated with deforestation. Secondly you are moving on to soils that are nitrogen-poor relative to grassland soils, hence you will need significant inputs of nitrogen each and every year which are not as necessary in the grassland system. And the IPCC factor for nitrous oxide emissions from N fertilizer is 1.25%. Then add losses of N_2O, which, as Rattan pointed out, has a global warming factor 296 times that of CO_2; it's easy to generate significant N_2O emissions from relatively infertile soils. So although northward expansion may involve yield increases, greenhouse-gas costs will be associated with it.

As climate change becomes more apparent, I think that all activities in our economy—certainly anything to do with agriculture—will be more and more evaluated in that light and any adaptations will be viewed accordingly, including adaptation and mitigation, such as adoption of carbon-sequestration practices. Adaptation will be the aggregate of thousands or hundreds of thousands of individual farmer choices. Jeff talked about this in terms of extension's role, but it's also the aggregate of individual farmer choices as influenced by policy and economics. Adoption of new seeding rates or cropping varieties will occur based on information presented to extension within the context of greenhouse-gas costs and associated economic potentials. And Linda Mearns talked about it yesterday. It's complex. For example, in Canada recently, the federal government announced that there will be a carbon benefit for adoption of no-till beginning from 2006. The many farmers in Saskatchewan who adopted it before 2006 will get no credit. The national balance benefits from it and Raymond talked about that yesterday; the decline in summer fallow contributes substantially to soil switching from a source to a sink. That no credit will be given from before 2006 may cause some perverse responses. Farmers may put things into a summer fallow to be able to get the benefit starting in 2006 and in future cropping years. Many farmers are very unhappy with that and Soil Conservation Canada has been active working against it. It's an example of a policy decision that will have an impact on the adoption of the mitigation measure and it may be a perverse impact compared to what they hoped to achieve.

The final point I would make deals with the complex response that several have talked about, and this morning we heard from one of the speakers that a second Green Revolution is needed. When you consider the need to feed the 9.5 billion people who will be on the planet by 2050 and the undeniable growth in modern biomass sources for energy, much more plant production will be needed. We all know that. Although the first Green Revolution, of course, was a tremendous success story, in some regions tremendous costs were associated with it. The point made effectively by Dr. Lal was that by considering the cropping system as a whole—the contributions of soil science, cropping patterns, crop development—we can avoid the deleterious impacts of the first Green Revolution as we advance the necessary Green Revolution of the future.

Angela Bedard-Haughn: Dr. Smythe?

Stuart Smythe: I don't think I can fill 5 minutes of discussion on this as I'm not a soil scientist. I did have the opportunity last week to listen to Derek Byerlee give a presentation on the World Bank's 2008 agriculture report, and I have a couple of observations to offer to the speakers for their insights. Forty years ago annual crop yields increased annually by about 3 to 4%. Those have declined down to on an average of about 1% for cereals. Byerlee also stated that fertilizer production will peak in 2017. Factoring in declining yields and fertilizing peaking in 7 or 8 years, if we look forward to a 2020 scenario, what will be the highest priorities for agricultural research and where will we go for funding?

Don Smith: Clearly, issues with nutrients and nutrient recycling need to be addressed related to fertilizers. We need to collect whatever is left from biofuel manufacture for nutrient recycling. In my view, phosphorus is the most important. There are alternatives for nitrogen. There's still a lot of potassium in the world, so phosphorus is going to be a big issue. Water is going to be a big issue. Energy will be an issue. Those would be the ones I'd pick. And let's not forget climate change.

Jeffrey White: You asked a good question about where we go to get the funding. More and more, this is a serious problem and in my own work I'm beginning to ask myself, "Who are my real stakeholders?" We keep talking about farmers, but I think maybe my stakeholders are industry representatives. In ARS[1] climate-change research, our big products have been for policymakers, such as IPCC-type impact reports, but we need to get to the growers' associations. Cotton Inc., which isn't for a food crop, is a good example. It has been responsive to our first contact. They realize that cotton farmers aren't going to make billions of dollars from carbon credits. They should be thinking more about what is the impact of climate change. There are opportunities there.

On the nitrogen issue, a big question is, "How much nitrogen usage has been wasteful just because nitrogen was undervalued?" As fossil-fuel costs go up or other things kick in to raise nitrogen cost, we will see farmers looking to more-efficient ways to use nitrogen, or they will change their crop mixes. In the United States, some farmers may get out of corn and go back to wheat if nitrogen prices dictate it. On the other hand, new nitrogen formulations are coming along, which may cost more but will make nitrogen use more efficient.

Rattan Lal: With rain-fed agriculture, where yields are declining or stagnant, one ton per hectare is a good yield in South Asia. In Sub-Saharan Africa, where rain-fed agriculture is normal, less than one ton per hectare may be expected on a national basis. Yields can very easily be 3 tons or 4 tons. Experimental yields are 5 tons, 6 tons. Getting from 1 ton to 3 tons in rain-fed agriculture, requires good soil and water. In sub-Saharan Africa, 5% of the land is irrigated. So, expansion of irrigation is needed, not only just with flood irrigation. I hope that we do not just waste water by that system, as is the case in South Asia and elsewhere. Drip sub-irrigation is desirable if that can be done, fertigation and condensation irrigation. We transport water as a liquid; perhaps it might be easier to

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[1] Agricultural Research Service of the United States Department of Agriculture.

transport it as a vapor and condense it directly on plant roots. That certainly is possible in terms of innovative technology. Once the water becomes available in sufficient quantity, nutrients would be of importance. As far as irrigated agriculture is concerned let's take the case of the Indo-Gangetic basin, with which I am familiar. Water tables are declining rapidly. Why are they declining? We are flooding rice in an arid environment. What do you expect? What happens in a sandy soil? So, the water tables are declining. Can we find a viable alternative? Someone talked about a cotton/wheat or maize/wheat system, neither of which is as economic as rice/wheat. Rice is a staple for the region. Can we find better ways to grow rice? Can biotechnology produce rice which, rather than needing flooding, can yield well under aerobic conditions? These are the kinds of interdisciplinary things we need to talk about. The June issue of the *National Geographic* magazine has an article on Punjab, and one thing you may notice is a large truckload of straw being taken to the markets. I see that whenever I go there. The wheat-straw price is 70% of that of grains. Tell farmers to add that back to the land to increase soil organic matter content and they will think you've gone crazy.

Regarding funding support, we must compensate these farmers for ecosystem sources that they provide to the world community. No handouts. No emergency knee-jerk approach of giving emergency aid to any community. These create corruption and kill morale. Let's pay them for ecosystem sources, for example for carbon sequestration to mitigate climate change. If farmers can be paid for carbon sequestration in soil which has many ancillary benefits why should he sell straw at the market? We can pay for ecosystem-source effects on water quality. We can pay for ecosystem-source effects on biodiversity. If we can develop a system that provides another income stream to farmers for doing the things that they are doing for society as a whole, so they are not given handouts, that is eventually the way to fund this kind of research on a long-term basis. In the short term, obviously we need donor support and we need our directors of experiment stations and deans and others to go to the bureaucrats in Washington to relate what research support we need from USDA. However, eventually it must be a self-driven system.

Carbon is being traded on the Chicago Climate Exchange at \$2.50 per ton, which is \$8 per ton of CO_2. You are talking about half a ton per hectare of carbon under the best-case scenario in Ohio and Midwestern United States. That roughly comes to \$2 per hectare per year. What farmer is going to get excited about having \$2 per hectare per year? If you take a kilogram of humus and analyze it for nitrogen, phosphorus, potassium, zinc and the water it can hold, it is worth about 40 cents at current prices. That's \$400 a ton. Yet, we are paying farmer \$8 a ton. That's undervaluing a very precious commodity, and undervaluing leads to abuse and misuse.

Bedard-Haughn: Questions from the audience?

Dorothy Murrell (University of Saskatchewan): Dr. Lal, you showed a picture of corn grown with continuous removal of residue vs. continuous return of residue, showing a night-and-day difference after a number of years. What does that say for biomass removal for fuel production? Is it wise to remove it, whether it's wheat straw or corn stover?

Lal: I wrote an article in 2007 titled *There Is No Such Thing as a Free Biofuel from Crop Residues*[1]. I do not believe in crop-residue removal. A couple of articles in *Science* talked about a billion ton biomass dream, of which 400 million tons would be corn residue from the Midwest corn belt. I think there would be a heavy price to pay if that were the case. Crop residue removal for biofuel production is not a solution. Not at all. Neither is converting tropical rain forests such as in Malaysia into oil-palm plantations for biodiesel. Considering the total ecosystem carbon pool, when you deforest you release 400 to 500 ton of carbon per hectare. An article by a colleague at Princeton estimated that it will take 132 years just to pay back the debt, not to offset it.

Where does the biofuel part fit here, in competition for land for food production? I mentioned yield stagnancy in rain-fed agriculture. We are going to need an additional 400 to 500 million hectares to meet the food demand by 2050. To meet a requirement of mixing 10% ethanol with gasoline will require about 800 million hectares of land for energy plantations. We don't have it. My advice to policymakers is to improve energy efficiency, and conserve energy by switching off the lights, adjusting the thermostat, carpooling, whatever. We can save anywhere between 25 and 40%. Sequestering carbon back into forests and soil as another part.

The long-term solution is to find a non-carbon fuel. The carbon age, like the stone age, will soon be over. During the carbon era, 1750 to 2100, we messed up the carbon cycle. We've got to restore that cycle. So, we've got to find a non-carbon fuel source, whatever that might be, maybe solar, maybe wind, maybe nuclear, maybe hydrogen, as long as the hydrogen is from water and not from fossil fuel or biomass.

So, to answer your question, many people talk about algal farms, perhaps cyanobacteria, and I think there may be few niches for that. It's possible to use large city grey water from Mexico or Delhi or Calcutta or Rio de Janeiro where you have lots of nutrients in water. It's possible to grow some algal biomass. It's possible to grow perhaps some halophytes with saline or brackish water irrigation to produce biomass, but to meet a 10% requirement from biofuel requires different thinking. Soil scientists, agronomists and policymakers need to sit down together and talk rather than just make a rhetoric statement yes we can take corn residue and make cellulosic ethanol. It's just not feasible. If you do a complete life-cycle analysis—and that is what is required—you will see that biofuels cannot meet the carbon requirement. The long-term solution is not biofuels.

George Wagner (University of Kentucky): Dr. Lal, biochar seems to be the latest popular magic bullet, and the notion is you can put it back into the soil without any consequences. I'd like your opinion of what those consequences might be.

Lal: Wim Sombroek was the secretary general of the International Union of Soil Science for many years and director of the Land and Water Division of the UN Food and Agriculture Organization, and in his young days he served as a soil surveyor in the Amazon and found that amongst the red soils, mostly oxysols, are patches of black soils very high

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[1] http://wwwtest.soils.org/about-society/presidents-message/archive/2.

in organic matter content. The Indian tribes were harvesting biomass and burning it and returning the ash and charcoal back on the soil, which was very productive. Rather than being sandy, the organic matter was increased along with nutrient retention and water retention. I saw the soil profile of that in a soil museum in Holland recently and those soils look excellent, beautiful, after thousands and thousands of years. Wim called them Indian black soils. Now, since that article was published, there has been a lot of movement that perhaps we need to do the same thing. A few experiments have been done over the last 3 to 4 years where we find that applying biochar generated through the pyrolysis process—burning biomass at 400 and 500°—we can convert some of that biomass into syngas or into liquid fuels and 30% of it could be converted to charcoal, which is an inert material. It has a high surface area and a high char density. Applying it to soil at about 50 tons per hectare increases organic matter content, and improves soil fertility. It's a great thing to do. I reviewed a grant proposal to put biochar into sand dunes of Saudi Arabia. Where are you going to grow 200 tons of biomass in Saudi Arabia in order to apply 50 tons per hectare? They are rich enough; they can acquire a glacier for water from somewhere. The UN is adopting a resolution to mitigate climate change with biochar in the Sahel. Again, where is the biomass coming from to produce 50 tons per hectare of charcoal? If the capacity existed to grow 200 tons per hectare of biomass, we would have no problem in the Sahel. The Amazon Indian tribes had all that forest around them and were able to do it. Now, that is not to say there are no niches. If we were close to a sawmill, it is definitely possible to take sawdust and convert that into biochar and use it. If you are next to a dairy farm in Ohio with 400 cows, take that manure and burn it to produce energy and convert it to biochar. You've got some niches, yet I have a problem. Two of my graduate students need a ton of biochar to put on small plots, 10×10 meters. I can't find it anywhere. If we were in India I'd find a rice mill where they burn the rice husks for conversion to biochar. So there may be a few niches, but to imagine that you are going to put 50 tons per hectare of biochar onto 2 billion hectare of land to sequester carbon in soil, think again.

Adekunbi Adeleke (University of Saskatoon): Biofuel production is very important. We can produce more yield to provide food for those that need it. And we can leave some crop residue on the soil and at the same time use some for biofuel production. My point is, everybody is needed. We need engineers, flex-fuel cars that use fuel more efficiently and we need plant breeders to produce plants that can use of nitrogen and water more efficiently. Soil scientists, agronomists, plant breeders: we all have to work hand in hand and there is no way we can do this without biofuels.

Lal: She's right. We need all them working together. She said it very well.

Malcolm Devine (Performance Plants): Jeff, you are the one who needs to answer this, because it's about maps with colored shady bits on them. It's a subject I've heard a lot about in the last 36 hours, so I consider myself a *quasi*-expert now. You made a comment that struck me and then you moved on from it very quickly. It was in relation to the spring wheat in North America. You had the band of spring wheat straddling the 49th parallel—a little bit below and most of it above—and with the typical climate-model temperature change, you said almost as a throw away comment, "As long as the soil can support it." I think about this a lot when I look at these colored maps and the red that's shifting up or the yellow that's shifting left or whatever it is. Someone is doing the climate stuff and the growing degree days, and whatever else that goes into all of this, and so the spring wheat will be better adapted 100 or 200 miles further north. But, is someone also looking at the ground level and below ground so that they don't produce a situation where the top half of the band now is overlying what is currently forest soil, relatively low pH, about 25 cm thick and there's 3 miles of solid rock underneath it, and you ain't going to grow a crop on it. Sometimes we see these things and think, "Well that looks good but, wait a minute, that's over the ocean now or that's in the Rocky Mountains." Help me bring these things together.

White: Certainly there are many good soil maps. But when I was at CIMMYT[3] doing these kinds of analyses, the big problem I found with maps was that they describe soils in terms of frequencies and similar things. The concept was that 60% of a soil in an area might be suitable, 30% less so and the rest just not suitable at all. Some good initiatives are trying to solve the soil-data issue, so that we have essentially the equivalent of the climate surface, but a soil surface, for the world. Pedro Sanchez is involved in this digital soil mapping of the world and I hope that moves ahead. In my analyses for winter-sown spring wheat in the south, I need to overlay that on land subject to irrigation. I would not want to show the map I put up to the governor of Arizona because he would say, "Oh great, a quarter of Arizona is going to be suitable for spring wheat soon," because the water is just not there. In fact, all scenarios show that the water is disappearing, but certainly the next generation of analyses have to bring a lot more rigor in. And then there are questions about seasonality. Monthly data, such as the coldest month, don't capture what's going on either. I see that in Arizona. We have some higher elevation sites that are good spring-wheat environments, yet they actually sow in March. If I used a growing-degree approach I could capture that difference, but if I just use coolest-month data they fall off the classification system.

Pennock: Tim Sutton from Australia made effective use of soil maps as well as real climate sequences. That's an example of using both good soil-resource information as well as realistic climate information to make sure that the plant product meets needs. But I agree that we don't see enough of that. Soil-resource information is out there. Someone at the CSIRO[4] effectively mobilized their soils people and their climate people and the plant people to ensure they were looking at all aspects of that. I don't think we do it very well in Canada. I can't speak to Arizona, but in Canada we simply don't use our existing

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[3] International Maize and Wheat Improvement Center, Mexico.

[4] Commonwealth Scientific and Research Organization, Australia.

information very well. The soil mapping in Saskatchewan cost millions of dollars and is largely unused for this kind of issue. I don't know why.

Claire Sullivan (University of Saskatchewan): I agree with Dr. Lal that sustainable soil management will create healthy communities, but I struggle with the fact that climate change is coming and world population is growing and our focus is largely on yields, relying heavily on fertilizers and other inputs to the soil. Dr. Lal talked about replacing whatever we take out. Organic would be the best way to do it, but he said that it would be a crime to tell farmers not to use inorganic fertilizers. But where do you fight greenhouse-gas emissions? Fertilizer production consumes energy and produces waste. Then you are saying that new varieties of crops will need fertilizer, so I am struggling with that.

Smith: You are right. Inputs are important in terms of achieving yield potential, but there is the issue of how much of any resource you can put in. One important resource is energy, and if you put in more nitrogen fertilizer, for instance, you are very tied to energy costs and if energy costs are rising you get into a bit of conundrum. Conservation is an important issue. Dr. Lal mentioned that. But my fear is that any reductions made here—and we should make them no matter what—may be offset by expansions in developing economies with no gain in the long run. We need to encourage conservation everywhere of course, but the problem may not go away just because of that. You can argue that if you produce biofuels you may be driving up the price of food, but if you don't provide some kind of alternative sustainable energy source, the price of food will rise anyway.

Lal: From 1900 to 2000, we did so many things on such a scale that if we were to repeat it between 2000 and 2100, we would need several more planets. When we talk about another 3.5 billion more people, what kind of lifestyle will those people have? We have to begin to think about how to decrease demands on natural resources. We seldom talk about that. We always say, "We are going to have 10 billion people. How can we double food production? How can we double the energy availability? How can we improve the efficiency?" But we don't talk about how we can decrease demands. It will not be possible for 10 billion people to live with the same standard of living as in North America and Western Europe. Somewhere along the line, we have to think about how to cut down on resource exploitation.

Food preferences: is it possible to sustain meat-based diets as currently, and is it even healthy to do that? Is it possible for the United States to continue *per-capita* energy consumption at the current rate? China's rate is a fifth of that and India's is a twentieth. Can China and India come to the same level of *per-capita* energy consumption as the United States? Does progress mean continuing to improve standards of living? We also need to think in terms of sustainable use of natural resources, not just in terms of meeting increasing demands. Where can we cut down the demand? Where can we reduce? Where can we recycle? Where we can do without? These are important questions for students to think about.

MODULE 4: ETHICS, POLICY, CARBON CREDITS

Ethical Issues in Agricultural Adaptation and Mitigation Responses to Climate Change

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I will explore ethical issues in agricultural adaptation and mitigation responses to the challenge of climate change, looking first at a secular ethical framework for knowing "what ought to be done" and then exploring resources in the world religions for doing what is right and good.

A SECULAR ETHICAL FRAMEWORK FOR KNOWING WHAT OUGHT TO BE DONE

Most North Americans think of themselves as following an ethical approach to life. What response from us to the challenge of climate change would be ethically right in our practice of agriculture? Tom Hurka (1993: 23) offered one schema argument for examining the consequences of our practices for people living in our own family, city or country, for people in other countries (especially in developing countries), for future generations (our children and grandchildren), and for the environment valued for itself (earth, air, water, animals and plants as having value along with humans). For us as individuals, corporations or governments, the decisions we make—as we attempt to deal with the challenge of global climate change and its human implications and take account of the economic factors involved—can be either ethically right or ethically wrong.

Ethics need to be distinguished from opinion. Surveys to determine what people think is right or wrong about climate change, for example, describe opinions rather than ethics. Too often, governments and industries make decisions based upon polls of people's opinions rather than on careful study of the ethical issues involved. Ethics is about *values* apart from people's opinions. Ethics assumes that some beliefs about right and wrong may be incorrect, and the study of ethics attempts to discover which are correct. In short, there is right and wrong above what people *think* is right and wrong, beyond people's opinions.

Ethical decisions require that we combine the scientific, social and economic facts relating to the threat of global climate change with general ethical principles that indicate right and wrong in all areas, and thus lead to specific policy recommendations. One can, of course, argue over which ethical principles should be employed in such an analysis, and the employment of different principles could lead to different ethical conclusions and different policy recommendations. This difficulty can be dealt with by selecting ethical principles that are not radical or speculative but are widely accepted by writers on ethics. In this way, the policy proposals developed by an ethical analysis can be convincing to most people. Using "an analysis of consequences of actions" as an approach, allows one to move from areas of least controversy and broad agreement (*e.g.* impact on own family and country) to areas where the policy conclusions are more radical and the agreement less general (*e.g.* impact on the environment). General policy decisions in response to the challenge of climate change can favour either adaptation or mitigation. With adaptation, we follow current agricultural practices, let global temperatures rise, and make whatever changes this requires: move people from environmentally damaged areas, build sea walls, and so on. With mitigation, we make every effort to stop warming from occurring, by reducing our use of fossil fuels, by using mitigating technology (*e.g.* hybrid cars) and by making lifestyle changes. As we shall see, ethical responses to climate change strongly favor mitigation over adaptation in individual, industrial or government decision making. However, it is unlikely that either pure strategy is possible. According to current estimates, pure adaptation would result in a temperature and sea-level rises that would be faster than any in the last ten thousand years, and would be devastating for many human, as well as animal and plant, communities. But pure mitigation or avoidance—reducing warming to zero—would be enormously expensive, or even (with population growth) impossible, to achieve. Therefore, an ethically acceptable goal will likely involve some mixture of adaptation and mitigation.

Adopting the ethical principle of considering the consequences of our actions means that if an act or policy has good consequences then this counts ethically in its favour, and if it has bad or disastrous consequences this counts ethically against it (Hurka, 1993: 24). But how does one decide which consequences are good? One popular principle from utilitarian ethical theory says that good decisions are those that maximize the best consequences so as to produce the greatest good possible. Other philosophers (*e.g.* Rawls, 1971) care not only about the total good a choice or policy will produce, but also about the breadth and equality of its distribution. A less demanding "satisfying principle" (from the idea of "making satisfactory") gives each of us "the duty only to bring about consequences that are reasonably good, either because these consequences are above an absolute threshold of satisfactoriness or because they represent a reasonable proportion of the most good the agent can produce" (Hurka, 1993: 25).

How do these ethical principles about "consequences" apply to decisions regarding climate change? Where actions such as burning fossil fuel and generating CO_2 foster global warming with its negative consequences, such as sea level rise displacing billions of people and destruction of animals and plants, it is clear that our ethical duty is to avoid such a result. If the result of allowing climate change would be disastrous, it is prudent to avoid this result even if we are not certain that it would come about (Hurka, 1993: 25).

In simple language, "better safe than sorry" applies when potential consequences of climate change are so serious. Now that we have a clear idea of how ethical judgments can be made by examining the consequences of our actions or policies, let us turn to questions of agricultural practice and lifestyle change—starting with our immediate family then widening our concern to include others elsewhere in the world, future generations and finally nature itself.

Consequences: Humans Here and Now

Of course, we all care about how climate change will affect ourselves, our families and our businesses. This is simply our own self-interest and does not really count as *ethical*. Our behaviour becomes ethical when we take decisions regarding climate change that will benefit and not harm others living in our neighbourhood, city and country. When we focus only on the present, and the effects of our actions on our families and businesses, cities and country, many of the most harmful results of global climate change seem not to count; for example, damage to the environment from a rise in global temperatures—killing organisms and ecosystems—does not matter according to this principle since only humans, not nature, have ethical standing. And since the most severe consequences of climate change may affect future generations, such harm is ignored by the "humans here and now" principle. Ethical analysis on the "humans here and now" principle tends to favour adaptation rather than avoidance or mitigation behavior—it does not foster change and simply sits still while climate change continues. It would, however, support technological mitigation measures such as increasing the efficiency of heating, lighting, cars, electricity-generating plants and the production of our food—as long as it did not cost too much. To reach an ethical approach that would argue for less adaptation and greater mitigation requires that we extend our concern for consequences out beyond "humans here and now" to the wider principle of "humans everywhere in the present."

Consequences: Humans Everywhere in the Present

This principle suggests that to maximize the good and be egalitarian in our ethics, we must be as concerned over the benefits and harms wrought by climate change in other countries as we are in our own. The effects of climate change on humans in all countries are included in our concern, but not the effects on future generations, which a more radical analysis would include. Extending the analysis to other countries strengthens some arguments for avoidance and mitigation. It suggests that as China, India, Africa, Latin America, *etc.*, industrialize, we in North America should help them by providing energy-efficient technologies (at costs they could afford). To be egalitarian about sharing the benefits of electricity, better food production and a higher standard of living means that we will likely have to alter our lifestyle and pay more for everything. To achieve this global benefit will cost developed countries like Canada and the United States more. But the result will be an increase in the standard of living for people in developing countries—an ethical result. Some sacrifice will be required in developed countries to meet the goal of enabling them to industrialize and achieve a higher quality of life, but with energy and agricultural efficiency so that additional CO_2 production and damage to the environment is minimized. The ethical challenge is to balance competing claims for equality among nations.

Consequences: For Future Generations

It is when we think of the effects of climate change on future generations in North America and elsewhere in the world that the realization of the need for mitigation from lifestyle change and altered agricultural practice is strongest. The predicted rises in sea level, the destruction of traditional habitats and industries and the loss of biodiversity push the ethically acceptable climate policy strongly towards mitigation rather than adaptation. We want to pass on a healthy environment and a sustainable world to our children and grandchildren. And just as an egalitarian ethical principle argues for equity between nations, so also we must ensure that there will be equity for future peoples—"seven generations into the future" to quote an Aboriginal teaching. When we factor in concern over global population growth, which threatens to increase in fifty years from six to ten billion people, the ethical challenge becomes very demanding. While we need to cut back in our consumption now to create opportunity for developing countries to industrialize, we also need to restrain ourselves even more severely if we are to create a lifestyle that is sustainable for large population increases in the future. Thus, the changes required include not only a reduction in patterns of consumption but also a reduction in the number of children we produce out of concern for equity for future generations.

Consequences: Nature Valued For Itself

We have widened our application of ethical principles from our own families and country to people everywhere and to future generations. But what about the environment, nature itself? In the recent past, our assumption has been that changes to the environment matter ethically only if human life is thereby affected. Even the 1987 Brundtland Commission report, which championed sustainability, boldly asserted that the wellbeing of people is the ultimate goal of all environment and development policies (World Commission on Environment and Development, 1987, p. xiv). A more radical view argues that we need to care for the natural world not just as a means to better human lives, but as an end in itself. When we adopt the ethical position of holding that nature has intrinsic value, the main problems to be dealt with are of two kinds:

- overpopulation by humans, which threatens to squeeze out other species and overwhelm the carrying capacity of the earth; and
- the rapid rate of climate change, faster in the last few decades than in previous history, which threatens many forms of life that require slower warming to be able to adapt successfully.

Thus, we are in danger of losing both individual species and whole ecosystems:

> *This will be bad both on an individualist environmental view—where individual animals and plants will suffer or find their natural life-activities impossible—and on a holistic view, where complex and fragile ecosystems, such as in the Arctic, the western prairies and the oceans, will disappear*
>
> —Hurka (1993: 32).

Concern for nature valued for itself leads us even more strongly to embrace the approach of avoidance or mitigation in our production of pollutants such as CO_2 that foster climate change. This ethical approach will require even more human sacrifice if ecosystems such as the Arctic or the southern prairies are to be preserved.

The ethical principles supporting the valuing of nature for itself can take several forms. Some argue that the pain and pleasure of animals has at least equal importance to the pain and pleasure of humans. Thus, climate changes that cause suffering to animals are to be avoided as are changes bringing misery to humans. Others value the flourishing of insects, fish and mammals, but argue that their value is less than that of humans because of our higher mental and rational capacities. A third approach, referred to as holistic environmental ethics, was given its classical statement by Aldo Leopold (1970: 262):

> *A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise.*

This approach takes the bearers of intrinsic value to be the wholes of nature of which humans are simply a part, *e.g.* ecosystems such as the fish in their ocean habitat in relation to human fishing communities and the climate that sustains them all. Such ecosystems can extend out to include the entire earth biosphere and, according to holistic ethics, grant humans, either as individuals or groups, ethical significance only as contributing to the harmonious working of the overall whole. In this view, if humans by their behaviour both overpopulate and overconsume, they may be in danger of being wiped out as a species to save the functioning of the ecosystem of the earth. In the holistic view, ethical standing belongs not just to individual organisms or species but to the interrelated ecosystem wholes that they compose. Let us now examine a world religion's ethics approach.

Ethical Resources in World Religions for Adapting Agriculture to Climate Change

Another source of guidance for making choices in relation to climate change and agriculture is found in the values of the world's religions. Although many North Americans are swayed by secular ethics, for Jews, Christians, Muslims, Hindus and Buddhists, their religious values, to a large extent, guide how they deal with questions of population growth (reproduction), consumption and the environment, which, as we have seen, are crucial factors in decision making with regard to agriculture and climate change. In the following analysis of religious values, we will focus on their teachings on what individuals, agriculture and governments can or should do, especially when it comes to genetic engineering, to make a difference in response to the challenge of climate change. Beyond Hurka's ethical principles (reviewed above), what are the added teachings offered by the major world religions to convince us that we are really interconnected with other humans and all of nature, and, therefore, we ought to take responsibility for the impact of our actions on other humans (living now and in the future) as well as on the animals and plants of the natural environment?

My sources for what follows are ethics theologians and layperson focus groups from the various religions all involved in the research of the Centre for Studies in Religion and

Society at the University of Victoria over the past five years. The lay focus groups have included scientists, government regulators, industry workers, animal-justice NGOs and private citizens.

Stakeholder views varied within and between focus groups, ranging from those that see all life forms as so strongly interconnected that species boundaries cannot really be identified (scientists, animal justice) to those who view animals as existing for human use and benefit (scientists). In a more modulated form, the latter anthropocentric position requires that although humans have a privileged position, still they must be good stewards, treat animals with respect, and not cause animals undue suffering unless essential for human health. In the religious traditions, this idea of the interconnectedness of humans and animals pervades the Eastern religions of Hinduism and Buddhism, while the model of human dominance with stewardship responsibilities characterizes the perspectives of the Western religions of Judaism, Christianity and Islam.

Interconnectedness of Humans, Animals and the Environment

As discussants in the agricultural scientists' focus group put it, there is a strong interconnectedness between humans, animals and the environment that is linked to feelings about the sanctity of life. This is indeed a good statement of the Eastern worldview manifested in the Hindu and Buddhist religions (Coward and Goa, 2004). The Hindu approach to animals is based on the notions of *karma*, *samsara* (rebirth), *ahimsa* (non-violence), and the presence of the divine in all beings (Narayanan, 2009). Animals, for Hindus, are human souls in different bodily forms. Eating an animal is, thus, quasi-cannibalism. Humans are reincarnated; they may have been animals in past lives, and they may be reborn as animals in future lives. Animals have no free choice, but humans do. Animals have to "burn off" bad *karma* they built up as humans over many lifetimes of making evil choices. Then they can be reborn as humans with free choice and the ability to move up or down "the ladder of being." Hindus also follow *ahimsa*, the doctrine of not harming any living creature, animal or human. For them, according to the *Bhagavad Gita*, the divine exists equally in all beings, animals, like humans, are viewed as manifestations of the divine leading to a deep sense of unity and respect for all life forms and their interconnectedness in the divine. Thus, early in Hindu history (*i.e.* before 200 BCE) hospitals for animals were established in India. This reverence for animals was also the view of Mahatma Gandhi and other contemporary Hindu leaders. As a result, millions of Hindus eat no fish, meat or eggs. Vegetarian practice is the ideal. However, many others do eat chicken and fish, but no red meat. Devout Hindus refuse to kill animals, but some will eat those killed by others.

Like Hinduism, Buddhism also assumes "the interconnectedness of all life." Buddhism adopts the worldview of *karma* and rebirth and the resulting ladder of existence on which animals (lower on the ladder) are beings like humans but in a different karmic form. Thus, Buddhists generally believe that they may have been an animal in a past life, and may be reborn as an animal in the future. All forms of life (humans, animals, plants, earth, air and water) are seen as interrelated and part of a much larger life-force, the Buddha Nature. To do harm or treat with disrespect any part of this entity (*e.g.* animals) is to harm oneself and all of life. Consequently, the Buddha taught compassion for all sentient beings. Animals, as sentient beings, are highly respected in Buddhist scripture and teaching. Also, like Hinduism, the ethical teaching of Buddhism stresses *ahimsa* or non-violence toward all living beings. As a general rule, Buddhists refuse to hurt or kill an animal, or to eat meat, though some do choose to eat meat.

According to Zen-Buddhism teacher Philip Kapleau, to kill or harm an animal is to violate the Buddha Nature, the sacred harmony that unites and is manifested in all organisms (Walters and Portmess, 1992) As for Hindus, eating meat is seen as a kind of cannibalism because of the *samsara* or rebirth presupposition.

Given the Buddhist and Hindu belief in the interconnectedness of humans, plants, animals and the environment, the use of animals in scientific experimentation is viewed as problematic. If humans engage in genetic modification of animals, from the Hindu-Buddhist perspective this would be acceptable only if there are clear benefits to animals and humans (which could include climate-change mitigation) that could not be achieved in any other way. Such must be done in a way that does not interfere with the happiness of animals nor make them any less able to progress up the ladder of being to rebirth as a human and eventual release (*moksa* or *nirvana*).

In Buddhism, the issue of motivation is key. If animal biotechnology is done for frivolous or purely commercial “bottom-line” reasons, that is unacceptable. As the Buddhist scholar David Loy puts it, the genetic modification of plants or animals for food or as a response to climate change, may be acceptable if it reduces suffering and if it is done with the intention of bringing about a good result (Loy, 2005, 2009). Loy questions, however, whether humans have achieved such a level of awareness regarding their own motivations.

Human Dominance over Animals but with Stewardship Responsibility

Unlike the strong interconnectedness perspective of the Eastern religions, the Western religions of Judaism, Christianity and Islam see the human-animal relationship as one of animals having been created by God to serve human needs, but with humans having a stewardship responsibility in this relationship. This viewpoint was strongly present in the Agricultural Producers focus group, which also emphasized the need for human stewardship and respect for animals and plants. As the biblical book of *Genesis* presents it, humans are created with priority over animals and plants, which are there to meet human needs. There is a clear hierarchy of being with humans at the top and animals and plants lower down. At the same time, plants, animals and humans are seen to be parts of God’s creation, all of which God blesses and sees as good. Therefore, humans in their stewardship responsibility are to minimize cruelty to animals, hence the *kosher* (Judaism) and *halal* (Islam) rules that are intended to ensure humane slaughtering of animals.

The mainstream attitude in Christianity until recently was that animals and plants are created by God for human use. As a participant in the Animal Justice focus group put it, *Genesis* teaches that humans have dominion over animals and are empowered to exploit animals to their own advantage, however they see fit. Unlike Muslims, Christians do not view animals as having an immortal soul. Christian views on these matters were influenced by the Greeks. In particular, Aristotle exerted influence over Augustine and Aquinas. Aristotle argued that nature made animals and plants for the sake of humans. Augustine followed suit, saying that animals and animal suffering are here for the physical and spiritual benefit of humans. Aquinas agreed, claiming that animals have no reasoning ability and no immortal soul. Luther likewise limited rationality to humans and further emphasized the power of human "dominion." (Linzey and Yamamoto, 1998: 65; Yarri, 2005).

This view is now being questioned by many Christian scholars, however, as a misreading of the Bible. Through the ages, there have been minority voices who have been advocates for animals, *e.g.*, Francis of Assisi (Yarri, 2005). In her recent reassessment, Donna Yarri argued that human dominion over animals should be understood as benevolent stewardship rather than autocratic despotism (Grant, 1999; Yarri, 2005). Many Christians now view plants, animals and humans together as parts of God's creation, all of which God blesses as good and inherently valuable. This view is validated in the first chapter of *Genesis* in which it appears that humans and animals lived together harmoniously as vegetarians, and in other Old Testament descriptions of an agricultural society in which domesticated animals were treated with respect and compassion. More recently, a new generation of Christian environmentalists has come to see humans as part of an ecosystem in which humans and animals are an interdependent part of nature, a nature created by God [see especially Wirzba (2003)]. The idea is that animals are suffused with God's Spirit (Nash, 1991: 117–121; Reuther, 1992: 247ff; Cobb, 1994: 173–180).

Regarding the use of animals in science, Andrew Linzey (1986, 1994:143–148), taking into account the above theological discussions, offered the following principles. Animals are not instrumental to human ends. Animals are not laboratory tools. Because animals are part of God's creation and interdependent with humans, the motivation behind our use of animals in science, agriculture, or as food must be carefully analyzed (as Buddhists maintain). Animals, like humans, are valuable *in themselves* by virtue of their creation by God. As stewards of creation, humans are accountable to God in how they use animals. Such uses must not be for human ends only, but for the good of the whole interdependent creation. In the teaching and life of Jesus, we find a compassion for animals and their pain, and in the Holy Spirit, a hope that as the world struggles toward a New Birth, animals, humans and all of creation may regain their original state of peaceful coexistence (Romans 8: 18–39; Wirzba, 2003).

Analysis of Animal Biotechnology Applications

Having outlined the worldviews of the major religions toward animals, we will examine the implications of these values and precepts for specific animal and plant biotechnology applications.

Applications to Improve Nutritional Quality, Disease Resistance and the Economic Efficiency of Food Production

A motivation expressed by many of those involved in genomic science and plant/animal biotechnology is that these advancements will benefit the poor and all of humanity by increasing the quality of food and the efficiency of global food production in the face of climate-change challenges. Participants in the Scientists focus group said that they are involved in agricultural biotechnology to achieve the greatest good for the greatest number. However, in the Animal Justice focus group, participants expressed that in our concern to help people we must not cause pain and suffering to animals. The Jewish religious tradition, with its twin values of *pekuach nefesh* and *tinkum olam* (saving human life and healing the brokenness of the world), supports such applications of animal biotechnology so long as the main motivation involved is not economic greed (Zoloth, 2009). For Buddhism, too, the major worry seems to be over motivation (Loy, 2009). For Hinduism, as Narayanan (2009) noted, aside from being proscribed from use in religious rituals or on holy days, many Hindus may welcome genetically modified foods, for examples chickens that produce more nutritious eggs, so long as there are no health hazards. Islamic scholars would follow Mohammad's example in leaving practical agricultural matters to be decided on the basis of their scientific and practical merits (Moosa, 2009). Thus, applications to increase nutritional quality and the economic efficiency of food production could be embraced, as long as the biotechnology in question did not increase animal suffering. If biotechnology applications help to increase the disease resistance or temperature/drought tolerance of animals and plants being raised for food, then this would reduce animal and human suffering and be judged a good thing.

Christians focus on the stewardship principle. One study in particular, *Engineering Genesis* (Bruce and Bruce, 1999), has examined Christian concerns in relation to the genetic engineering of animals. The book's key issue is the extent to which we are justified in intervening in the lives of animals for our benefit. While cruelty toward animals is clearly not acceptable, the use of biotechnology to increase milk production or to produce a therapeutic protein in milk is considered ethically acceptable. But respect for animals requires that they be seen as more than mere supermarket commodities or generators of bigger profits for producers and retailers. The authors expressed an additional worry that the introduction of animal biotechnology will further foster large-scale agribusiness approaches globally that will force small farmers out of business. Similar concerns were raised by the World Council of Churches in its 2006 report on genetics and agriculture (WCC, 2006). Its worry is that the introduction of GM animals in agricultural will reduce biodiversity and result in the loss of the cultures and the traditional knowledge of indigenous peoples and small farmers in developing countries along with our ability to respond to climate change. From this perspective, there is real danger that agricultural biotechnologies, as used by the market economy, may actually exacerbate problems of injustice and violence for the world's poor (WCC, 2006: 32, 72). Most adherents to religions would agree that concerns such as these, along with worries over causing pain and suffering, must be carefully weighed when the potential benefits of animal biotechnology are being considered.

Reduction of Negative Environmental Impacts

Some stakeholders noted that humans have the capacity to control a lot of what happens in our world, for good or evil. Whereas consumer demand for products such as hamburgers, that drives the clear-cutting of Amazon forests in order to produce more cattle for beef, leads to a bad result (increased global warming), the creation of the Enviropig, engineered to have less phosphorus in its manure and thus be less destructive to the environment, is an example of a technology designed to produce a good result (Golovan *et al.*, 2001). The Eastern religions of Hinduism and Buddhism, with their focus on the strong interconnectedness of humans with nature, would agree. The Western religions of Judaism, Islam and Christianity with their stewardship ethic, would also take a favourable view of applications that help to reduce negative environmental impacts and foster the mitigation of climate-change effects. Another example would be the engineering of trout to have a biomarker chip that will detect pollution in streams so that such human-generated problems can be better detected and regulated (Koop *et al.*, 2008). A further use of such engineered trout will be to more effectively test streams to see if their water is safe for human consumption, thus avoiding health risks, an application likely to find support in all religious traditions.

The Industrial Manufacture of Animals and Plants: Transgenics

Industrial agriculture uses the process of transgenesis to move a gene that expresses a desirable trait from the same species or another species into the genome of an animal that will then manifest that desirable trait. Resulting animals may be engineered to grow larger and/or more quickly (*e.g.* transgenic salmon), be less damaging to the environment (*e.g.* the Enviropig), be disease or drought resistant, or produce less methane.

Among Jewish scholars, there appears to be considerable support for the transgenic modification of animals, since it does not appear to be in violation of the prohibition against crossbreeding (*i.e.* it does not entail a sexual act between members of different species), and the "grafted element" (the moved gene) takes on the identity of the species into which it was grafted, so that there is no significant change of appearance. The *halakhic* (Jewish Law) issue at stake is the identity of the resulting genetically engineered entity, which depends in large part on its physical appearance. Although scholars admit that there is still ongoing debate, the consensus seems to be that the status of a cow, for example, that has been modified by genes derived from a pig, is still a cow as long as its general appearance is not changed. In effect, the identity of the "grafted" pig gene becomes submerged in the identity of the animal (in this case the cow) into which it has been placed. In discussions regarding genetically engineered poultry, the conclusion is that such chickens are *kosher* provided they exhibit the physical criteria of an identifiable species of *kosher* fowl—in other words, that they still look like chickens. Further, even when an animal has received genes from a non-*kosher* animal, it is permitted as food as long as there is no manifestation of the non-*kosher* gene donor. Given this argument, Jews would have no problem eating transgenic salmon.

In Islamic Law, the debate over transgenic animals rests on the question of whether humans have taken on the power of creation through genetic engineering. From this perspective, it would seem that transgenics are acceptable, since none of the elements *(i.e.* the genes) used in transgenics are human-made—Allah created them—and since no change occurs in the birth of the animal or in its natural stages of creation as given by

Allah. For Islam, then, according to these scholars, transgenics, like cloning, can neither be called "creation" nor even a partnership in creating, and is, therefore, judged to be acceptable. However, the production of transgenic animals must also be shown to be in the best interests of human society, to be useful in the mitigation of climate change, and must not cause harm to animals (Qasmi, 2003).

Christianity seems to take a more guarded approach to transgenic animals than either Judaism or Islam. Andrew Linzey (1986), a professor of theology and animal ethics at the University of Oxford argued that animals, like humans, are valuable *in themselves* by virtue of their creation by God. As co-creators or stewards of God's creation, humans are accountable to God for the ways in which they use animals. Such uses must not be for human ends only, but for the good of all creation. From this perspective, the transgenic modification of animals goes against the God-given natural biodiversity of life. The presumption that humans know what is optimum for selection from the vast diversity and complexity of traits in an animal is an act of hubris. (This critique would seem to also apply to ordinary selective breeding.) Therefore, the use of transgenics in routine animal production to side-step normal breeding methods on the grounds of economics or convenience is not acceptable. However, transgenic applications such as the Enviropig, which foster human-animal interaction for the good of the environment and the mitigation of climate change, may be seen as acceptable.

Buddhism, in its analysis of transgenic applications, also focuses on the motivation involved. According to the Buddhist scholar David Loy (2005: 4), transgenic animals are not good or bad in and of themselves; it is the human motivation in developing and using them that matters. The Buddhist understanding of *karma* is that actions motivated by negative intentions tend to bring about adverse consequences, while actions motivated by good intentions tend to bring beneficial results. If our eagerness to develop and use transgenic animals is motivated by generosity, loving kindness and wisdom, which could include the mitigation of climate change, we can conclude that this technology is likely to bring good results. If, however, we are motivated by greed, ill will and delusion or ignorance, then we should expect this new technology to increase, rather than reduce, our suffering and frustration (*dukkha*). This Buddhist approach does not imply that any GM technology is bad in itself. Rather, it is our problematic and confused motivations that tend to lead to negative consequences. Loy offers a Buddhist rule of thumb: "Is our interest in developing transgenic animals due to our greed or ill will; and…can we become clear about why we are doing this? Among other things this means: do we clearly understand how this will reduce *dukkha* [the suffering of humans and animals], and what its other effects will be?" (Loy, 2005: 7). Loy doubts that we have reached such clarity of intention and understanding in our current industrial agricultural biotechnology.

Where Religions Draw the Line

As the religions consider the issues raised by genomics, genetics, and applications to animal biotechnology, places where they would "draw the line" are beginning to emerge. For Muslim scholars, any frivolous application or one that would alter the natural identity of an animal is rejected as a human usurpation of Allah's role. In both science and biotechnology, all use of animals must be shown to be required by human necessity and to minimize pain upon the animals involved (Masri, 1986: 192). In Judaism, the Talmud and other authorities are clear that animals are to be fed before humans eat and are not to be worked on the Sabbath, when they must be free to roam the fields. This last requirement would seem to run strongly counter to modern factory farming practices. According to one authority, the crowded, confined and inhumane ways food animals, such as chickens, are farmed makes it questionable whether or not they can be regarded as *kosher* regardless of how they are slaughtered (Regenstein, 1991: 194). However, here the overriding ethical principle for Judaism is that care and kindness to animals is for the higher purpose of humanizing humans in their relation with each other, rather than primarily out of concern for animals. The Talmud specifically rules out crossbreeding of animals. But, as we have seen above, transgenesis in animals has been found by Jewish scholars not to violate the crossbreeding prohibition or to significantly alter the natural identity of animals (*e.g.* the "cow-ness" of cows or the "chicken-ness" of chickens).

In Christianity, earlier thinkers such as Augustine, Aquinas and Luther all emphasized the principle of human dominion over animals, in which animals are seen to exist only for humans' physical and spiritual benefit. Aquinas allowed that cruelty to animals is sinful, but was mainly concerned that cruelty to animals may lead to cruelty toward humans. Due to the theological shift taking place with the advent of Christian environmental ethics, however, humans are now seen to be part of, rather than separate from, nature. Historically, this may have its roots in St. Francis's love for animals. However, Albert Schweitzer started the modern shift with his extension of Christian love to include "reverence for all of life" and the requirement that humans, if they cannot refrain from killing animals, must at least be ecologically respectful and just in such killing (Nash, 1991: 117–121). Rosemary Reuther (1992) noted that creation-centred theologians such as Norman Wirzba, Matthew Fox, Teilhard de Chardin and Alfred North Whitehead offered Christian theologies that overcome the human/nature dichotomy as well as the separation of nature from God. The American Methodist theologian John Cobb, Jr., (1993: 172) described God as sacramentally or even incarnationally present in all of nature. He wrote:

> *To think of all... living things as embodying Christ must give us pause. A creature in whom we see Christ cannot be only a commodity to be treated for our gain or casual pleasure.*

If all are in Christ, observed Cobb (1994: 178), then in some way our treatment of animals is a reflection of how we treat Christ. Such a view clearly rules out any frivolous or instrumental use of animals. It also brings the Christian worldview with regard to animals very close to those of Hindus and Buddhists. Cobb concluded that this realization does not mean that Christians will suddenly be able to stop harming animals. But the recognition that like us, animals are in Christ, will lead humans to wrestle with problems related to their suffering that could result from climate change. For Cobb, any application in science or animal biotechnology that causes suffering is ruled out.

In contrast with the one-life orientations of Judaism, Christianity and Islam, the presuppositions of *karma* and rebirth lead Hindus and Buddhists to see the question of where to draw the line in a quite different light. Since animals may have been humans in past lives, and will at some point be reborn as humans in the future, the use of animals in science or agriculture should be viewed with the same ethical restrictions one would use if they were human now. In scientific experiments, this means animals deserve the same health, safety and intrinsic-value considerations one would give to humans. In agriculture, the implication is that while animals can aid humans by pulling ploughs, for example, or providing dairy products, they should not be used for food, hence the vegetarian ideal. And whereas the Western religions have agreed to the sacrifice of animals in a laboratory environment for human-health benefits, the Eastern religions are much more reluctant to accept such treatment of animals. Not only is it seen as tantamount to engaging in the imprisonment and killing of beings with souls, but such treatment of animals will, in the Eastern view, also result in suffering in future lives for all of the humans involved (Chapple, 1986). The resultant suffering will not only be visited upon individual scientists, but upon the society that allowed animals to be used in processes in which their intrinsic nature as future human beings is ignored. Evidence of these consequences can already been seen in the negative aspects of science that now plague the world, such as death and disability from adverse drug reactions (*e.g.* the thalidomide tragedy), increased militarization, and ecological destruction from unsustainable agricultural practices (*i.e.* human violence upon the soil, air and water).

Buddhists express similar concerns about the future results of genetic experiments upon animals. While such activities may help to relieve human suffering in this life, from the Hindu/Buddhist long-term perspective of being reborn over and over until one reaches *nirvana* or enlightenment, such efforts pale into insignificance and are not worth the added suffering (*dukkha*) they bring to the scientists, animals and the societies involved. Thus, says the Buddhist scholar Christopher Chapple (1986), in the case of whether to use animals in scientific research, the three considerations of intentions, means and consequences would need to be considered in each situation. Many current uses of animals would be deemed unnecessary. Only in exceptional cases would the intention be deemed acceptable, such as the testing of a vaccine desperately needed to prevent an epidemic. The mitigation of the potentially devastating effects of climate change could also be included here. The means employed would have to ensure that pain to the animals is minimized, and the consequences considered: will lives of humans and animals, in fact, be saved? Will unintended reactions such as genetic damage, increased cancer risks, or the loss of biodiversity also occur? Such considerations, when used with care, would constitute a reasonable approach to evaluating the use of animals in biotechnology applications for some Hindus and Buddhists. Others, however, would reject altogether any attempt to justify animal biotechnology.

Areas of Agreement

Having reviewed how various religious traditions draw the line, let us conclude by briefly noting areas of agreement. All religions would seem to share a common conviction that frivolous applications of animal biotechnology such as the glowfish, cosmetic research or the cloning of pets, are seriously questionable from a moral point of view. There is also a common focus on motivation, especially in the Eastern traditions of Hinduism and Buddhism. If the application is meeting a real human or ecological need (*e.g.* the mitigation of climate change) it may be seen as acceptable. However, if it primarily reflects individual or corporate greed or a scientific drive to be first (hubris, vanity), then it is not viewed positively by any religion, nor indeed by the majority of the stakeholders interviewed for this study. Finally, the concern that the *telos* or species integrity of animals may be challenged by some kinds of genetic modifications was raised in the stakeholder focus groups and by the theologians of many religions. Doing such things as described above to animals, which are divinely created, generates a sense of abhorrence among lay people and a view that humans are overstepping their stewardship limits when they change the essential nature and identity of an animal. The religions are just beginning in their analysis of genetic applications and have yet to compare them with other alternatives that would, for example, be just as effective in meeting environmental challenges. For example, Tariq Ramadan (2009: 233), arguably the leading scholar of Islam in the West, said that reflection about respecting the environment or about how animals should be treated is virtually non-existent in Islam.

Policy and Regulatory Concerns from the Religions' Perspectives

Like NGOs, animal-rights groups, ethics committees and various secular publics, members of religious traditions comprise a wide segment of civil society and have distinct ethical views about animal and plant biotechnology that deserve to be included in public-policy and regulatory-decision making. In considering the acceptability of biotechnology, religious traditions address a broader spectrum of concerns than just scientific and regulatory issues. Religions tend to focus on moral issues, such as the place of animals and plants in the natural order, which the formal discourses of law and science typically rule out of bounds. Religious perspectives on the relationship of humans and animals depend on a number of presuppositions concerning the divine order of creation, the nature (*i.e.* soul, rationality) attributed to animals and the manifestation of the divine in and through them. As such, the genetic modification of animals, whether for research or commercial purposes, raises ethical concerns that are very important to followers of these traditions.

Religious views and beliefs about animals and plants are typically expressed in the form of dietary restrictions. In North America, with its multicultural and religious diversity (representing all of the religions discussed here), there is strong interest in clear and detailed labelling of commercial food items sufficient to give consumers the ability to select those that do not violate their religion's food prescriptions. For example, Hindus and Buddhists practising the vegetarian ideal of their traditions must be able to be confident that what they are purchasing and eating contains no animal materials. The same is true for secular vegetarians. Christians who hold theological convictions about the genetic modification of animals—for any one of the reasons discussed earlier—may wish to avoid genetically engineered foods in any form. Consequently, clear labelling seems especially important in a country such as Canada where freedom of religion is specified in the Canadian Charter of Rights (1982). As one member of the Health Researchers focus group, who self-identified as a Christian, put it, "My church creeds talk about respect for nature. That pervades what I do in my work…and I think it pervades policies for the protection of human health that the Canadian government implements."

In a recent study of the acceptability of genetically engineered foods for members of religious traditions, Conrad Brunk, Nola Ries and Leslie Rodgers gave special attention to the regulatory implications of religious dietary practices (Brunk *et al.*, 2009). Responding to the views expressed by groups of lay people from the major religious traditions, they drew the following conclusions:

- Nearly all religions have beliefs that place limits on the production, preparation or consumption of food. These practices will manifest themselves in consumer acceptance of new food technologies.
- For these religions, DNA is ontologically and ethically significant. Thus, transgenes from animals considered impure or inappropriate for consumption may constitute a "contamination" of foods into which they are transferred, and are likely to be met with rejection by consumers.
- Religious adherents need information not only as to whether a product contains genetically engineered organisms, but also about the source of any transgenic material.

Brunk *et al.* (2009) concluded that it is "incumbent upon regulators of food technology to establish mechanisms that require public access to the information about the origin of any transgenes in genetically modified products." The dietary concerns of these religious communities or their concerns over climate change, fall within the fundamental rights of religious and moral conscience to which a liberal democratic society should ascribe special weight and respect. The same applies for secular vegetarians.

Conclusion

In this presentation I have described secular and religious ethical perspectives that can be engaged in evaluating agricultural responses to climate change.

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Adapting to Climate Change: The Challenges and Opportunities in an Uncertain Policy Environment

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Global climate is changing and the scientific community has concluded that the warming is unequivocal (IPCC, 2007) as seen in atmospheric and oceanographic temperatures, rising sea levels and the loss of sea and land ice (Zwiers, this volume[1]). By comparing the influences of natural processes in driving climate change with the combination of natural plus human processes, it can be concluded further that humans are the main cause of this warming. Based on knowledge of the climate system and its relationship to human-generated emissions of greenhouse gases, it is projected that the climate will continue to warm at about the same rate as over the past 25 years, for the next 20 to 40 years, as it adjusts to the already accumulated additional greenhouse gases in the atmosphere, plus those expected to be added over that time. Depending on the global emission-reduction strategies that are undertaken, the climate beyond about 2040 will become increasingly dependent on the emission scenario and the rate of warming will either decrease, a little or considerably, or slightly increase, for the range of likely future emissions. The climate will continue to change and the warming will continue for centuries to follow (Weaver, 2008).

Although Canada signed the Kyoto Protocol in 1997 and ratified it in 2002, our emissions of greenhouse gases have continued to rise (Environment Canada, 2008) such that, in 2007, they were 34% above the accepted Kyoto target of 7% below 1990 levels for the period 2008–2012. In 2007, energy-related emissions accounted for 81% of the total, and agriculture contributed 8.6%. The impact of agriculture on climate change through its emissions has been discussed by Desjardins (this volume[2]).

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[1] Pages 19–26.

[2] Pages 29–38.

The impact of a changing climate on agriculture is the subject of the chapter by Mearns[3]. As the climate changes with overall warming, there will be significant regional variations, generally with winters warming more than summers, land areas more than oceans and coastal zones, and higher latitudes warming more than nearer-equatorial latitudes (Christensen *et al.*, 2007). Variations in future precipitation and resulting water supplies will be regionally and seasonally dependent with some areas of the world having reduced wintertime precipitation, some reduced summertime precipitation, and some both. The results will have implications for water availability, agricultural productivity and overall food supply.

This chapter is about adapting to climate change and its challenges and opportunities in an uncertain policy environment. Although climate-change adaptation is usually defined, as it will be later in this chapter, as (IPCC, 2007b):

> *...adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.*

I have chosen to define, for purposes of this chapter, adaptation to climate change as actions and adjustments taken both to reduce agriculture's vulnerability to a changing climate and its extremes and to reduce the impacts resulting from emission-reduction actions, responding in both cases to policies, regulations and other factors. Climate change is a multi-dimensional issue—it has cultural, social and economic values and is much beyond an environmental issue. Because of the multitude of perspectives and issues, there are fundamental disagreements on approach (Hulme, 2009), which lead to uncertainties. There is a need for improved communications from science to policymakers (McBean, 2009b). A focus in this paper will be on how can or will the implementation of climate-change adaptation take place in recognition of these uncertainties—uncertainties both in future climate and in the present and future policy environments.

The Policy Environment for Adapting to Climate Change

The international policy environment for agriculture's role in climate is based on the United Nations Framework Convention on Climate Change (Climate Convention) (UNFCCC, 2009). The Climate Convention's objective is, as stated in its Article 2:

> *...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure food production is not threatened and to enable economic development to proceed in a sustainable manner.*

Note that ensuring continuity of food production is one of the criteria.

Under the Climate Convention's Article 4 on Commitments, all parties are expected to undertake cooperative actions in the development of technologies to reduce anthropo-

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[3] Pages 41–45.

genic emissions of greenhouse gases. Among the sectors specified are agriculture, forestry and waste management. The Climate Convention also includes actions on preparing for climate adaptation, including plans for water resources and agriculture.

The Climate Convention's Kyoto Protocol, as signed and ratified by Canada and most other states (but not the United States) has emissions-reduction targets that are usually the focus of policy considerations and national programmes that include strategies to "mitigate climate change" (Article 10). Under the Kyoto Protocol's Article 2, commitments include development and use of renewable forms of energy, which could include renewable energy from agriculture. In Annex A, which specifies the sectors/source categories for emissions and emission reductions, those for agriculture include:

- enteric fermentation;
- manure management;
- rice cultivation;
- agricultural soils;
- prescribed burning of savannas; and
- field burning of agricultural residues.

The Kyoto Protocol also includes commitments (under Article 2) to promote sustainable forms of agriculture and to "facilitate adequate adaptation to climate change" with agriculture, forestry and waste management among the sectors specified. Among the plans for adaptation are technologies and methods for improving spatial planning, which could be interpreted to include planning for different agricultural-production zones.

In late 2009, the 15th Conference of the Parties under the Climate Convention will be convened in Copenhagen. It will address the directions laid out in the Bali Action Plan that countries agreed to in 2007 at the 13th Conference of the Parties. The Action Plan specified steps to be taken to "enable the full, effective and sustained implementation of the Convention through long-term cooperative action, now, up to and beyond 2012," which is after the end of the Kyoto Protocol commitment period. An agreed long-term global goal for emission reductions, to meet the Convention's objectives, is to be one outcome of the 15th Conference of the Parties, as well as interim targets. What those targets will be or even if there will be agreement on them, is uncertain at present. From an agriculture point of view, there will likely be important terminology, guidance and rules in the details. These details are even more difficult to predict.

Canada/United States Federal-Policy Environment

Now, in mid-2009, a rapid transition is occurring in Canadian and the United States climate-change policy, as a result of the change in the US administration with its proactive position on global warming [see McBean (2009a) for one commentary]. Correspondingly, there is a flurry of activity in Canada to develop policies on emissions reductions as well. Perhaps the most important new action is the American Clean Energy and Security Act (often referred to as the Waxman-Markey Bill), which is in negotiation in Congress at the time of writing. A broadly based (covering more than 80% of US emissions) regime is expected, based on cap-and-trade principles, which may be in place as early as 2012. Downstream electricity emissions and upstream natural-gas liquid, petroleum and coal-based liquid fuel producers/importers are the focus of the first phase. By 2014, downstream industrial sources (including process emissions), but not including petroleum or biomass, will be brought into the system, with regulations for mid-stream natural-gas local-distribution companies coming in about two years later. Opinions on the Waxman-Markey Bill are widely varied, including conservative views that it will be a very costly and ineffective instrument and some environmental groups saying it has so many loopholes that it will not be effective in emission reductions. It is, in any case, a very complex bill—about 1,000 pages [see, for example, Wall Street Journal (2009)].

Until now, most of the action on greenhouse-gas emissions reductions in the United States has been at the state level. The Western Climate Initiative (WCI, 2009), which involves many western US states, differs in scope from, but uses the same thresholds as, Waxman-Markey. British Columbia, Manitoba, Ontario and Quebec are partners with seven US states in the WCI, and Saskatchewan and Nova Scotia are official observers.

The Canadian federal government, signalling a desire to align with the United States, has declared that its initial-phase policy will cover electricity and industry, and will be phased in in a similar way to the US/Canada's Climate Change approach (Environment Canada, 2009a). It aims to reduce total greenhouse-gas emissions by 20% from 2006 levels by 2020, and by 60 to 70% by 2050. These are slightly larger cuts than the US targets. The regulatory framework will impose mandatory emissions-reduction targets across the full spectrum of Canadian industry. Full details are yet to be released. From what is presently known, there is mixed alignment with the US bill. One difference is the emphasis on a Technology Fund as a compliance mechanism. The federal government has stated that it is open to provincial equivalency. The minister also laid out his principles for the Canadian position for the Copenhagen Conference of Parties in late 2009:

- balance environmental progress and economic progress;
- a long-term focus;
- technology (with a focus on carbon capture and storage); and
- a consensus at Copenhagen that has to involve both the developed world and the developing world.

With respect to the focus on carbon capture and storage, it is important to keep in perspective its limitations and costs (*e.g.* Economist, 2009)

On June 10, 2009, Minister Prentice announced *Canada's Offset System for Greenhouse Gases* (Environment Canada, 2009b), which is intended to provide Canadian firms and individuals with the opportunity to reduce or remove emissions from activities and sectors that will not be covered by planned greenhouse-gas regulations. Offset credits will be issued by the Offset System for eligible greenhouse-gas reductions or removals achieved from a specific project. One offset credit represents 1 tonne of carbon dioxide equivalent emissions reduced or removed. This will establish a price for carbon in Canada and the government will issue offset credits thereby creating a "currency," a means of exchange, which can be traded like commodities or stocks.

Canada's Carbon Offset Policy may be an opportunity for agriculture. The opportunities for offset projects include:

- capture and destruction of methane from landfills;
- reforestation and other forestry projects; and
- agricultural-soil management.

Biological sink projects, which either remove greenhouse gases from the atmosphere and store them in reservoirs (for example, in soil or trees) or avoid emitting greenhouse gases to the atmosphere from a reservoir (for example, avoided deforestation) will generally be relatively slow accumulations of carbon and it is possible that the results will not be permanent and greenhouse gases may be re-released. Agriculture sink projects could include the following types of land-management practices:

- reduce the intensity of tillage operations;
- adopt crop rotations and grazing-management practices that sequester more carbon in the soil; or
- increase the use of permanent cover.

There will also be other types of biological sink projects such as afforestation—creating a forest where none has existed since at least 1990—and reforestation.

Canadian agricultural soils have been a source of atmospheric carbon dioxide for the past century due to depletion of soil carbon through cultivation. A trend towards no tillage in western Canada, primarily for economic reasons, has helped return carbon to soils. It is now predicted that Canadian soils will soon become net sinks, but there is need for enhanced scientific understanding of the processes and improved means to quantify and verify emissions.

As yet, Canadian and American emission-reduction policies are neither fully clear nor enacted, so considerable uncertainty remains. Adaptation to these policies and evolving with them will be a challenge. Will the credits for changing agricultural practices to enhance carbon sequestration be sufficient to justify them? With the changing climate, how will mitigation (emission reductions and/or carbon withdrawal) regulations be compatible with changes in crops and other practices more appropriate to a future climate and a future market for food?

Climate Change and Food Security

The Climate Convention's objective was to avoid dangerous interference with the climate system. A fundamental question is, "What is dangerous?" The European Union and some states have adopted the target of 2°C warmer than pre-industrial global temperatures and the recent Climate Congress in Copenhagen (University of Copenhagen, 2009) reconfirmed this objective. The Congress concluded that:

> *Temperature rises above 2°C will be difficult for contemporary societies to cope with, and are likely to cause major societal and environmental disruptions through the rest of the century and beyond.*

Parry *et al.* (2008) analysed the impacts on various sectors from different levels of emission reductions. Although a 50% reduction by 2050, based on meeting the target of 2°C relative to pre-industrial temperatures (or 1.4°C compared to 1980–1999 values), seemed to avoid dangerous impacts, they noted two additional points. First, with the uncertainties involved in such projections, which are skewed towards larger changes, unacceptable impacts are possible. Second, because the climate system is still not in equilibrium with the emission reductions, one must really look at the impacts at 2100, with their associated uncertainties. Estimates of the overall costs and risks of climate change have been estimated by Stern (2007) to be equivalent to losing at least 5% of global GDP each year, now and forever. Taking a broader view of risks and impacts could raise that to 20% of GDP or more.

As we look towards the future it can be expected that, in the next few decades, there will be decreases in production for some cereals at low latitudes while there will be increases for some cereals at mid- to high latitudes (Parry *et al.*, 2008). In the latter half of this century, as the climate warms and changes further, there will be decreases in all cereal production at low latitudes and decreases as well in some regions in mid- to high latitudes (IPCC, 2007b) . The impact of climate change on global agricultural gross domestic production (GDP) by 2080 is estimated by the IPCC (2007b) as between –1.5% and +2.6%, with considerable regional variation. Overall, mid- to high-latitude agriculture stands to benefit, whereas agriculture in low latitudes will be adversely affected. Parry *et al.* (2008) further commented that:

> *We are now probably witnessing the first genuinely global effects of greenhouse gas warming. The steep increases in food prices around the world are the result of rising costs and demand aggravated by drought in food-producing regions—in the case of Australia, probably due in part to global warming and by a poorly conceived experiment in climate policy that has converted cropland to bio-fuel plantations. This should serve as a wake-up call: impacts of climate change can surprise us, especially when they act in combination with other pressures.*

Several countries have identified climate change as a security risk. For example, the German Advisory Council on Global Change (2008) identified what they termed a conflict constellation as climate-induced declines occurred in food production. They noted that, already, more than 850 million people are currently undernourished and this will worsen as a result of climate change. Their analysis led to the conclusion that for a 2°C increase in global mean temperature (relative to pre-industrial values—about 1.4°C more warming) there will be a food *insecurity* increase in many developing countries. For 2 to 4°C warming, there would be a drop in agricultural productivity worldwide, which would be reinforced by desertification, soil salinization and/or water scarcity. Food "hotspots," from a security point of view, were identified in several places around the world. The Canadian national climate assessment (Lemmen *et al.*, 2008) has also identified the implications of climate change for Canadian activities related to international development, aid and peace keeping.

The impacts of changing climate are already evident in every region of Canada (Lemmen *et al.*, 2008) and in North America in general (Field *et al.*, 2007), and climate change will exacerbate many current climate risks, and present new risks and opportunities, with significant implications for communities, infrastructure and ecosystems. It has health implications (Séguin, 2008) and the impacts of recent extreme weather events have highlighted the vulnerability of Canadian communities and critical infrastructure (Berry *et al.*, 2008). Since climate change will have impacts elsewhere in the world, and, accordingly, these regions will take some adaptation measures, there will be implications for Canadian consumers, and the competitiveness of some Canadian industries, including agriculture.

Reducing Agriculture's Vulnerability to a Changing Climate and its Extremes

The national assessment (Lemmen *et al.*, 2008) concluded that general adaptive capacity in Canada is generally high, but is unevenly distributed. Resource-dependent and aboriginal communities are particularly vulnerable and this vulnerability is magnified in the Arctic. Some adaptation is occurring in Canada, both in response to, and in anticipation of, climate-change impacts. Examples of these adaptations are integrating climate change into existing planning processes, often using risk-management methods that are seen as an effective approach. There are, however, barriers to adaptation action that need to be addressed, including limitations in awareness and availability of information and decision-support tools. Although further research will help to address specific knowledge gaps and adaptation-planning needs, there is the knowledge necessary to start undertaking adaptation activities in most situations now. What is missing in most cases is a policy framework and national and/or provincial comprehensive adaptation strategies. When and how they will arise and what they will include are uncertain.

Adaptation strategies for a changing climate are necessary (Burton, 2008) and will need to be an ongoing process. The national assessment (Lemmen *et al.*, 2008) defines adaptation as:

> *...making adjustments in our decisions, activities and thinking because of observed or expected changes in climate, in order to moderate harm or take advantage of new opportunities.*

Although climate hazards pose a potential threat, their associated impacts are largely determined by a community's vulnerability, which is a function of its exposure to those hazards, its sensitivity to the stresses they impose and its capacity to adapt to these stresses, and the central goal of adaptation policy must be to reduce vulnerability (Burton *et al.*, 2002). The vulnerability of communities to extreme weather events is not a fixed condition, and can be reduced through actions that minimize exposure, reduce the sensitivity of people and systems, and strengthen the community's adaptive capacity. It is also useful to go into the disaster-risk-reduction terminology to note that a hazard is (UN ISDR, 2009):

> *...a potentially damaging physical event, phenomenon or human activity that MAY cause the loss of life or injury, property damage, social and economic disruption or environmental degradation.* (emphasis added)

Conditions of vulnerability are determined by physical, social, economic, and environmental factors or processes that increase the susceptibility of a community to the impact of hazards. Disasters result when there is the intersection of a hazard and vulnerability. For our discussion, the hazards are those generated by a changing climate and, hence, avoiding disasters necessitates actions to reduce vulnerability.

Climate-Adaptation Policy

Impacts are largely determined by a community's vulnerability, which is a function of its exposure to climate hazards, its sensitivity to the stresses they impose, and its capacity to adapt to these stresses (Henstra and McBean, 2009). That vulnerability can be reduced through actions to:

- minimize exposure;
- reduce the sensitivity of people and systems; and
- strengthen the community's adaptive capacity.

Four factors contribute to achieving adaptive capacity:

- access to information;
- expertise with information, analyses and translation of information into policy;
- fiscal capacity; and
- political will to act.

Designing adaptation policy for climate change requires, *inter alia*:

- assessments of the effectiveness, costs and feasibility of measures to reduce vulnerability;
- stakeholder analyses to identify targets and beneficiaries of adaptation interventions; and
- analyses of the consequences of inaction.

Research and development are underway to address these issues of design. However, there are clear difficulties with regard to fiscal capacity as at least some level of public expenditure will be needed and that will be limited by competing demands on scarce economic resources. In the end, a critical issue will be generation of the political will to act, which will most likely come with more general recognition that adaptation is necessary and possible, and that it is desirable to adapt.

As noted earlier, the international policy regime of the Climate Convention and its Kyoto Protocol include statements on needs for adaptation. The Bali Action Plan of 2007 moved climate-change adaptation more to the forefront. One section is on the need for "(c) Enhanced action on adaptation." The Bali Action Plan calls for:

- international cooperation to support urgent implementation of adaptation actions;
- risk-management and risk-reduction strategies, including risk sharing and transfer mechanisms such as insurance;

- disaster-reduction strategies and means to address loss and damage associated with climate-change impacts in developing countries that are particularly vulnerable to the adverse effects of climate change;
- economic diversification to build resilience; and
- ways to strengthen the catalytic role of the Convention in encouraging multilateral bodies, the public and private sectors and civil society, building on synergies among activities and processes, as a means to support adaptation in a coherent and integrated manner.

Concluding Remarks

What issues might an adaptation-policy regime consider? As the climate changes, there will be stresses on agricultural production in some regions and opportunities in others. Will there be financial and regulatory support for diversification into other crops and for possibly relocating agriculture production to other areas? If so, in the latter case, will there be investments in public infrastructure, such as transportation and water supply, to support the new region? In the case of water supply, some regions of Canada will become very water stressed and there will be conflicting demands for whatever water is available. Will regulatory regimes favor or be a disincentive to agricultural production?

Canadian adaptation policies are in development at least in some provinces (*e.g.* Ontario), but they are clearly not at the forefront of major political thinking on climate change, which continues to be focussed on emission reductions. It is important to recognize that choices made now will have continuing economic and social impacts for a long time. Choices on emission-reduction strategies will have impact on the global climate of 2030 and beyond. However choices for cap and trade, offsets and the rest of the various instruments for reducing emissions will have impacts as soon as they are implemented. Based on recent announcements, it seems likely that emission-reduction policies will be in place by, or possibly before, 2012. Adaptation strategies are needed in all sectors to adjust to these policies and to take advantage of favorable rules and regulations. With the continuing uncertainty as to what those policies will be, the agricultural community needs to be flexible and resilient.

Choices on adaptation strategies for the impacts of climate change are needed now as changing climate is already having impacts. The chosen strategies will have impacts on local economic and social activities within Canada as soon as they are effectively in place. In this case, there is uncertainty of the details of the changing climate, *e.g.* how much change and frequency of occurrence of extreme events. Implementation of adaptation strategies will require some investments—fiscal capacity—and the political will to act.

It is essential that climate change be recognized as the long-term issue it is, and that it cannot and should not be put aside whenever another seemingly more important and immediate issue appears on the scene. It is an issue of intergenerational and international equity that must be given appropriate attention. Remember (Sauchyn and Kulshreshtha, 2008):

> *We have options, but the past is not one of them.*

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Greenhouse Gas Emissions Offsets from Agriculture: Opportunities and Challenges

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As the scientific evidence of global climate change continues to accumulate (IPCC, 2007) and the predicted impacts of a warming planet become more widely known, national policies and international agreements designed to mitigate global warming have sought to strike a balance between environmental sustainability and economic achievement. Under the 1997 Kyoto Accord (hereafter "Kyoto") a global framework for reducing greenhouse gas (GHG) emissions to pre-1990 levels was developed that established binding emissions reduction targets and timetables for industrialized countries, and included flexibility provisions intended to reduce the overall cost of emissions reductions. Countries subject to emissions limits were free to decide how to reduce emissions to meet the established targets over the period 2008–2012. Countries could design their own domestic policies to meet their targets. Kyoto's flexibility provisions allowed cooperation between industrialized countries to achieve emissions reductions through Joint Implementation and included the Clean Development Mechanism (CDM) to facilitate cooperation with developing nations that were not subject to binding emissions reductions. Despite the fact that not all countries ratified the 1997 agreement, many countries, provinces, and states have, in the time since Kyoto, enacted policies individually or in cooperation to reduce GHG emissions. In addition to binding regulatory approaches taken by governments there has also been at least one similar voluntary initiative undertaken by the private sector in the form of the Chicago Climate Exchange.

CAP AND TRADE

Economists have taken a strong interest in helping governments to evaluate various policy instruments to achieve emissions reductions. On the basis of the success of the United States' sulfur dioxide (SO_2) emissions trading program and a large body of scientific research on regulatory standards, emissions taxes, and tradable pollution permits (Hanley *et al.*, 2007), policy designs that establish enforceable property rights to verifiable quantities of emissions, which are transferable between parties, have been pursued most frequently and are the focus of the majority of ongoing national and international policy debates. This type of policy design is commonly referred to as "cap and trade" because the government establishes a "cap" on total emissions, allocates permits that constitute individual property rights to emit an allowable quantity of a pollutant, and allows firms to trade these "allowances." An allowance typically entitles its owner to one metric ton (tonne) of carbon dioxide equivalent (tCO_2e) emissions. The total emissions cap is expressed in terms of millions of tCO_2e ($MtCO_2e$) and the sum of all individual allowances equals the emissions cap or target.

Each firm subject to the emissions cap must have allowances to cover their total level of emissions or they are subject to fines or other penalties enforced by the government. To achieve required emissions reductions, a firm must either reduce its emissions or acquire allowances to cover its total emissions. Firms can reduce their own emissions by reducing output, operating more efficiently, and/or by investing in less C-intensive technologies. These options can become very expensive for anything more than modest reductions in emissions. Because different firms operating in many sectors of the economy use different technologies, they have different GHG abatement costs and there are potentially significant gains from trade if regulated firms are allowed to exchange emissions allowances in a market. By allowing firms to trade allowances, those with the lowest abatement costs can abate more pollution than required and sell excess allowances to firms with higher abatement costs. This allows society to achieve the desired environmental objective at a lower total cost than if all firms were only allowed to generate emissions equal to the amount of allowances they hold (whether grandfathered or auctioned to them) and no trade of allowances were allowed.

All else equal, a more stringent emissions cap will place greater pressure on all firms operating under the cap and is expected to result in greater demand in the market for allowances; this will have the effect of driving up the market price of allowances and, thus, firm compliance costs. Many factors in cap-and-trade program design can influence the overall cost to society.[1] Including mechanisms that give firms time to develop and transition to less C-intensive technologies and energy sources reduces the overall cost while increasing the political feasibility of a cap-and-trade policy. Typical mechanisms that achieve this include phasing-in a cap through gradual reductions over several years,

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[1] One of the most notable factors that determines the overall cost of a cap and trade program is whether allowances are freely allocated or auctioned to firms (Burtraw *et al.*, 2001). This topic is outside the scope of the current paper.

allowing firms to "bank" low-cost emissions reductions achieved in early years to be used to meet more stringent reduction requirements in the future, and allowing regulated firms to pay for GHG emissions reductions by unregulated sources that have the effect of offsetting emissions released by the regulated firm. The third of these mechanisms is called an emissions offset, and is the focus of the remainder of this paper.

Agriculture and forestry are two of the most commonly considered sources of offsets in an emissions trading market because these sectors of the economy are not directly regulated and have the potential to adjust management practices in ways that sequester additional C or otherwise reduce emissions of the GHGs methane (CH_4) and nitrous oxide (N_2O) (IPCC, 2007; EPA, 2005). Discussion of forestry offsets is left to other authors and agricultural offsets are the focus of what follows. The remainder of this paper discusses potential sources of GHG-emissions offsets that represent *opportunities* for agriculture under policies that seek to limit global warming and the scientific and policy *challenges* that must be addressed in order for agricultural offsets to be an effective tool in mitigating human impacts on climate.

OFFSETS AS OPPORTUNITIES FOR AGRICULTURE

The three main GHGs that can be mitigated through agricultural activities are CO_2, CH_4 and N_2O. Agricultural management practices can be altered or changed in many ways to reduce emissions from existing practices, to enhance the removal of CO_2 from the atmosphere (C sequestration), or to displace emissions from fossil fuels by using crops or residues as sources of energy (IPCC, 2007). Displaced fossil fuel emissions from bioenergy crops represent an important opportunity for agriculture and remain a fertile topic for research as governments continue to rely on renewable fuel standards as an important component of energy and climate change policies. Fossil fuel emissions displaced are not treated as a source of offsets under cap-and-trade policies and we turn our attention to the biophysical and economic potential of reduced emissions from current practices and sequestration.

Reduced or more precise application of nitrogen (N) fertilizer or livestock manure can reduce N_2O emissions if greater N-use efficiency can be achieved. Methane emissions from livestock can be reduced by improving feeding and manure management practices (*e.g.* by covering lagoons or capturing CH_4 through use of anaerobic digesters). Increased feeding efficiency can be achieved through the use of dietary additives that suppress methanogenesis or improved forages, and opportunities for manure management, treatment and storage that reduce CH_4 emissions both represent mitigation options in livestock management (IPCC, 2007; Smith *et al.*, 2008). Atmospheric C can be sequestered in the soil and in vegetation. Soil management practices that increase sequestration include conservation tillage (*e.g.* mulch till, ridge till and no till) and crop residue management (Lal *et al.*, 1998). Vegetative C storage can be enhanced through perennial grass plantings and grazing management (Follett *et al.*, 2000). Although existing agricultural practices already play a role in mitigating the global warming effect of some fossil fuel emissions that result from fertilizer production and fuel use, there is considerable potential to expand and improve upon existing practices. This potential for wider use of mitigating practices is what creates the *opportunity* for farmers to sell emissions offsets in a market for CO_2-equivalent emissions.

An important aspect to keep in mind when evaluating different mitigation options is the distinction between the technical potential and the economic potential that individual agricultural practices represent (McCarl and Schneider, 2001; Smith *et al.*, 2008). Technical potential refers to the biophysical ability of various management practices to reduce emissions, but does not take into account the cost-effectiveness of the same practices. In moving from the science of C sequestration and CH_4 capture to thinking about the adoption of new cropping or manure management systems, it is necessary to take into account whether there are adequate incentives for farmers to adopt mitigating practices. We can expect farmers to adopt these practices only if the costs of implementation are covered by the benefits received.

Under a cap-and-trade program, farmers can sell offsets to regulated emissions sources to cover the cost of these practices, but economic analysis of cap-and-trade policies to date suggests that, even at the highest prices per tCO_2e considered, only a subset of the mitigation options that have technical potential are economically feasible (McCarl and Schneider, 2001; EPA, 2005; Smith *et al.*, 2008). The global technical mitigation potential by agriculture in 2030 has been estimated to be as high as ~5,500 to 6,000 $MtCO_2e$/year; this is in contrast to the global economic potential, which has been estimated for the same year to be as low as 1,500 $MtCO_2e$/year for a carbon price of US\$20/tCO_2e and as high as 4,300 $MtCO_2e$/year for a price of US\$100/tCO_2e (Smith *et al.*, 2007).

It is also important to consider non-agricultural sources of offsets like forestry and landfill gas when assessing the potential role of agricultural offsets. The economic analysis done by the US Environmental Protection Agency (EPA) (2005) to assess the domestic C-sequestration potential of forestry and agriculture found that for market prices over US\$30/tCO2e, the economic incentives are such that crop and pasture lands are expected to be converted to forests because the sequestration potential of forest exceeds soil-C sequestration and high prices cover the cost of land-use conversion. Over the higher range of prices considered, agricultural soil C has lower relative economic potential than afforestation. This is one illustration of why agriculture should not be analyzed in isolation from other sectors that can supply offsets. It is also important to consider both domestic and international sources of offsets (if available) because the demand side of the market is seeking to minimize its cost of compliance and it stands to reason that if country "A" can supply the offsets needed for compliance at a lower cost than country "B," the lowest-cost source of abatement will be exhausted before firms consider paying for higher-cost alternatives.

The main economic motivation for including offsets as part of a cap-and-trade policy to reduce GHG emissions is to reduce the overall cost of achieving the emissions target or cap. Economic analysis of cap-and-trade legislation is perhaps the best place to look to see the estimated effect of including offsets on the cost of allowances, and thus the overall cost of achieving a GHG emissions target. Recent analysis of the draft American Clean Energy and Security Act of 2009 (H.R. 2454) by the United States Congressional

Budget Office found that the inclusion of both domestic and international offsets has "a significant effect on allowance prices" and decreases the market price 69% in 2012 to US$35 compared to when offsets are not a compliance option under the legislation (CBO, 2009, p. 16). The EPA's economic analysis of the same legislation similarly found that "offsets have a strong impact on cost containment" and that "without international offsets, the allowance price would increase 96%" to US$25–34 in 2015 (EPA, 2009a, p. 3). Both analyses of the most recent federal cap-and-trade legislation in the United States illustrate how incorporating offsets into a cap-and-trade program may influence the cost of climate change mitigation.

Scientific research has demonstrated many opportunities for agriculture to supply emissions offsets in a market for GHG emissions, but researchers and policymakers must always be mindful of the relative abatement cost of alternative sources of both domestic and international offsets when evaluating different policy designs. The market price of allowances will ultimately determine how big a role agricultural offsets will play in emerging markets.

Scientific and Policy Challenges to Offset Effectiveness

The fact that science has demonstrated the potential for agriculture to provide emissions offsets under a cap-and-trade program and that including offsets as part of policy design may significantly decrease the cost of such programs is not enough to ensure the environmental integrity of legislation or international agreements that aim to mitigate the effects of climate change. To focus readers' attention on some of the most substantive issues that must be addressed in order for agricultural offsets to be an effective component of a regulatory (non-voluntary) cap-and-trade program, I will address four principal dimensions of policy design:

- Verifiability,
- Enforceability,
- Additionality, and
- Permanence.

Verifiability

In order for agricultural offsets to be credible emissions reductions, they must be verifiable. There must be scientifically valid techniques or methods capable of quantifying the amount of actual emissions offset by every single individual management practice (*e.g.* no-till or livestock methane capture) that is allowed under the offset policy established by a cap-and-trade program. It must be possible to verify that practices have been installed on every single farm, and monitoring or auditing must occur to ensure that practices are implemented or maintained consistent with the protocol established for each practice. Verifiability encompasses the technical ability to verify the amount of emissions that have been offset by a given practice and specific protocols must be established at the outset so that market participants know how quantification of CO_2e will be performed.

Verification will necessarily involve a third party that is not involved in the farm operation and is in no way associated with any entity serving as an aggregator of offsets undertaken by many individuals. Because maintaining an offset registry could potentially entail working with many tens of thousands of individual farmers located in many states or countries, many of the details involved in commoditizing the sequestered C or captured CH_4 involve significant transaction costs that must be carefully managed in order for the operation of an offset registry to even be feasible. It is important to note that the cost of using third party services to audit management practices or coordinate large groups of farmers so that they can access the market must be borne by the parties involved and, when this cost is added to abatement cost for a specific practice, it increases the market price required to incentivize emissions offsetting practices.

Enforceability

In order for emissions reductions to be credible, they must be enforceable. This means that legal contracts between farmers and the offset registry or third party aggregator must be established to clearly spell out the responsibility of all parties involved and the duration of the contract. It is likely that multi-year contracts will be required to entice farmers to change tillage practices, plant perennial grasses or make capital investments in manure-handling or -treatment systems, and this is discussed further under the permanence dimension below. The consequences of violating the contract must also be clearly spelled out to ensure that emissions reduction obligations are fulfilled, otherwise the environmental integrity of the cap-and-trade program could be called into question.

Enforceability may be a particularly important consideration for dealing with the inclusion of international offsets in a domestic cap-and-trade program. This may limit the ability of countries with particularly poor property rights or legal systems to participate in an emissions market if it is not feasible to enforce the provisions of the required contract. To the extent that third parties can help to overcome this potential obstacle, greater cooperation between industrialized and developing countries like that envisioned by the CDM in the Kyoto Protocol will be possible. Because the marginal abatement costs for farmers in developing countries are considerably lower than for farmers in industrialized countries, international offsets typically play a disproportionately large role in reducing the overall cost of cap-and-trade programs, as detailed in analyses of the Waxman-Markey cap-and-trade bill being considered currently by the 111th US Congress (CBO, 2009; EPA, 2009a)

Additionality

All agricultural practices adopted that offset GHG emissions must be in addition to any practices the farmer would have adopted in the absence of cap-and-trade legislation that would pay them for emissions they offset. The point of reference is some baseline level of "business as usual" activity and the way that such baselines are established must be determined *ex ante*. Dealing with additionality is one of the most difficult issues in the design of offset programs because a large number of farmers have already undertaken these practices for a variety of reasons that may or may not have included the potential to be paid for soil-C sequestration in the future. The 2009 Waxman-Markey legislation allows offset projects that exceed the activity baseline established and that were undertaken after January 1, 2001, to be included if the offsets were registered under some other program recognized by the administrator of the EPA.

Additionality may ultimately lead to unintended consequences if the financial incentives of being paid for offsets are great enough. Consider that under the US EPA's revised [since EPA (2005)] baseline emissions scenario used to analyze the draft Waxman-Market bill there are already enough acres under conservation tillage that agricultural soil-C sequestration starts in 2010 as a net C sink of 77 $MtCO_2e$ compared with being a net source of 32 $MtCO_2e$ when estimated in 2005 (EPA, 2009b). This represents a nearly 100 $MtCO_2e$ in emissions difference that is largely attributable to increased adoption of conservation-tillage practices. If these farmers were to plow up all of these acres after a cap-and-trade program is enacted, only to turn around the following year and re-establish their conservation tillage so that their practices are eligible to be compensated as offsets, this would release the vast majority of the sequestered C back into the atmosphere, thus negating any mitigation previously achieved. This seems like a potentially significant unintended consequence, but one that is altogether reasonable to expect if early adopters are not eligible to receive offset credits. This is related to the issue of permanence.

Permanence

Because some agricultural practices that offset GHG emissions are reversible, as is the case with soil-C sequestration, adoption may not represent permanent removal of the offset emissions as would be the case if a regulated source reduced its emissions by an equivalent amount. Permanence has been dealt with in many ways that include the provisions in the contract already described under the enforceability dimension that detail how reversion is handled. Among other things, this may rely on offset credits placed into a "reserve pool" when offsets are credited to farmers based on the GHG and practice adopted. This practice has been used by the Chicago Climate Exchange (www.theccx.com) and the government of Alberta (www.carbonoffsetsolutions.ca) in issuing the only such agricultural offset credits awarded through functioning emissions markets to date. Emissions offset by agricultural practices may be discounted so that the number of marketable credits generated is less than the estimated amount of sequestration that occurs to account for the frequency of reversion among certain practices. For example, 1 tCO_2e may be placed into the reserve pool for every 5 tCO_2e sequestered so that for every 5 metric tons removed from the atmosphere, farmers are eligible to sell 4 tCO_2e. This discounting or credit-issuance rate is done to address permanence and the reserve pool that can be drawn on to maintain the overall environmental performance of the emissions market.

Permanence is a key reason why agricultural offsets are often viewed as a tool to bridge the gap between the present and the time when new technologies and fuel sources can be developed that achieve emissions reductions that are not subject to the same challenges. By lowering the cost of reducing emissions in the near term, offsets can help reduce the overall cost to society of transitioning away from fossil fuels and developing new technologies.

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Dr. Gramig previously worked in a consulting setting as part of an interdisciplinary team of researchers developing environmental risk management products for livestock manure lagoons. He worked with extension agents, commodity groups, farmers, environmental organizations, government agencies that oversee agri-environmental programs and elected officials while employed in the Governor's Office of Agricultural Policy in his home state of Kentucky. He completed his PhD in agricultural economics at Michigan State University, and his MS in agricultural economics and BS in natural resource conservation and management are from the University of Kentucky.

Ethics, Policy, Carbon Credits

Panel Discussion and Q&A

Moderator: Jill Hobbs
University of Saskatchewan
Saskatoon, Saskatchewan

Panelists:

Murray Fulton
University of Saskatchewan
Saskatoon, Saskatchewan

Richard Gray
University of Saskatchewan
Saskatoon, Saskatchewan

Darrell Corkal
Agriculture and Agri-Food Canada
Saskatoon, Saskatchewan

Murray Fulton: We heard from Gordon McBean about the importance of policy and what can happen if there is uncertainty about it. Benjamin Gramig then talked about some of the important things to consider as we design policy specifically on economic factors—some of the costs and bureaucratic aspects likely to be entailed. Harold Coward gave us some things to think about in terms of ethical considerations that might go into a policy decision. I'd like to say comment on the meeting in December in Copenhagen that has been mentioned, at which an attempt will be made to come up with a new international framework for dealing with climate change. It's particularly interesting to think about Copenhagen occurring when the world is going through a major financial crisis. Debates and discussions are going on around what should the economic order look like; people are questioning capitalism in the twenty-first century. There's a very interesting article by Joseph Stiglitz, the Nobel Prize winner, in the July 2009 issue of *Vanity Fair*. Stiglitz says that there is a danger that this economic crisis will encourage protectionism. More importantly, he suggests that we need to look back at some of the policies that have governed the international monetary system over the past 30 or 40 years, and see how it was organized and in whose interest it was organized. He concludes that the developed world—and, in particularly, its large national institutions—have been the primary beneficiaries of the international monetary system.

I'll use this as a jumping off point to talk about Copenhagen and subsequent meetings, and what we will see in terms of international climate-change policy. If we can take a lesson from the financial system, I think that greenhouse-gas policy will be drafted in a way that is going to benefit certain groups and it's interesting to think about who those groups might be. I suspect that they will include large energy companies. I expect that some of the larger agricultural biotech firms will also be among the players. We also need to think in terms of countries; are we witnessing a period in which the influence of the West—particularly of the United States—is being lost to other countries, in particular India and China. Will they put their stamps on this new policy environment in a way that fundamentally changes things? One of the speakers mentioned that developing countries want to "stick it to" the West for their policies over the last 20 or 30 years, and my guess is that, for the most part, they will have difficulty doing that. However, I also suspect that countries like India and China will play a role in a way that we haven't seen before. The current economic crisis is one of the ways by which they will be able to get their foot in the door

Richard Gray: This issue of forming policy in the area of greenhouse gases will not only be a challenge in the short run, it will be a dramatic challenge in the long run. We are a long way from where we need to go. I'll raise two issues. There's a lot of interest in cap-and-trade systems amongst the large emitters. This relates to Murray's question; if, in fact, these large final emitters are allocated permits, they can actually profit and make higher returns on these systems. It's not necessarily an imposition. If they have to purchase permits they are going to be worse off. If they are given their allocations they can actually benefit from these systems. What's interesting with the cap-and-trade system is that consumers are generally left out of the picture. The refiners, for example, would have to have permits for the energy they consume in refining gasoline. But most of the energy is still left in the gasoline, and the consumers themselves are the ones who are going to have to make the decision to use less gasoline. I just came back from Europe. The price of gasoline is double what it is here, which equates to a $200-per-ton carbon tax. It's been that way for a long time and you can see some differences in the systems. They use energy more efficiently, they use public transportation more, and cars are more efficient. On the other hand, the differences in the systems are not enormous; conservation is also needed there. We have tremendous opposition to any kind of carbon tax. People believe in reducing greenhouse gases, but they resist paying some of the price of getting there.

Just a note on carbon sequestration: I think it is important to think about options where we don't treat carbon sequestration in pools as necessarily permanent. The political and economic realities are that contracts just don't go out that far, and probably too much risk is implied in a contract that supposedly goes out that far. However, there is still value in storing something for a period of time and, rather than view it as purchase of permanent storage, rental of temporary storage is a better way to think about these carbon contracts. They shouldn't be valued the same as permanent storage, but we need to develop mechanisms that don't necessarily tie things up for a long period of time or would do so only through repeated contracts.

Darrell Corkal: I'm with the Ministry of Agriculture, in the Agri-Environment Services branch, but my fundamental organization is the Prairie Farm Rehabilitation Administration. We have a physical sciences and social sciences project, and I want to emphasize what Harold Coward was saying: we need to look at the ethical and social consequences of climate change. What's been fascinating about the study is how the physical and social sciences have been linked together. We know when John Palliser came here in 1857–1859 for a survey of the prairie region, he said that it wasn't fit for habitation; he concluded that, we now know from tree-ring data, because he came at the end of a prolonged period of drought, probably 10 to 15 years. Government policies, provincially and federally, established prairie settlements in the early 1900s. Interestingly enough, some 500 years of tree-ring data suggest that such multi-year droughts in the prairies are recurring. Of course, you have wetter-than-average years and drier-than-average years, but the multi-year droughts are the problem. How did we as a society adapt to that? Well we created organizations like the Hanna Special Areas Board and the Prairie Farm Rehabilitation Administration at the time when Canada was suffering its greatest economic and ecological impact. The "dirty 30s" had a serious impact on the country. We were going through a world economic crash then as well, and the government of Canada was spending half of its budget on relief. We established a successful agriculture in the prairies by taking advantage of moisture retention in the clay soils. So, technical solutions were related to that. Institutional adaptation created organizations to help people understand and link the agronomy in water management to soil. Having said that, we are not completely free from vulnerability to drought. In their report on the effects of the 2001–2002 drought in Canada, Elaine Wheaton and Suren Kulshreshtha stated that a larger area of the country was affected than by the drought in 1931. The impact to the country's economy was a $6 billion drop in GDP, with a loss of 41,000 jobs. However, the ecological impact on resources wasn't major because it lasted only 2 years. Our management strategies allowed us to cope with a 2-year drought. If we were to get a 5- to 8-year drought or an 8- to 10-year drought, as the tree-ring data suggest we might, the questions we are facing are: "Will we be able to cope and how will we adapt?"

And this is where we come back to Harold's comments. We must consider not only the technical aspects and the economic aspects, but also the social impacts. There's a trend globally towards integrated water-resource management. Even the term "stewardship" is being used in organizations' names such as the Manitoba Water Stewardship Organization. The notion of managing water and our resources by incorporating the stakeholders' and citizens' statements is increasingly gaining favor. How will governments, federally and provincially, manage that and actually allow stakeholders to have a say? There's an increasing consensus about the need to move to a technocratic paradigm with a hazard-centered interest in geophysical processes into one that emphasizes the mutuality of hazard and social conditions. Harold talked about what the consequences of our actions are. We also must consider the consequences of not acting.

Malcolm Devine (Performance Plants): Dr. Coward, I enjoyed your presentation. My question concerns comments you made about your discussions with religious leaders from different faiths, Judaism, Islam and Hinduism, and their views on transgenic plants and animals. I'm not sure whom you are speaking to in the Christian world. I assume it's not the Pope. The Vatican has a quasi-academy of sciences that recently met to discuss this whole topic. They gave their considered opinions, which you reflected to us; how do their opinions relate to those of the Catholic in the street, the Hindu in the field, the common man if you like? Is there a relationship? Because, whatever the lead Judaic scholars say that as long as the "cowism" of the cow is still there it's okay, if I run into a Jewish colleague and ask him, he might say, "No way." Can you comment on that?

Harold Coward: When we do the research in each tradition, we don't go to religious leaders like the Pope, in any of the traditions. We go to ethics theologians or scholars in the tradition, who have actually done work on the question, read the science, thought about it. In Islam they get the lawmakers together with Muslim scientists and try to come up with a position. And you are quite right: the leaders come up with positions that very often are miles apart from what the lay people say. I mentioned that we had focus groups as well, of lay people from each of these traditions. And we had separate focus groups of lay people who were scientists, lay people who were in animal-rights groups, lay people who were regulators, government regulators, and so on. We tried to get a cross-section of lay people, so it wasn't just the ordinary chance person in the street, but included those actually engaged with the issues. Take the Jewish example that you mentioned. The Halakhah Jewish law scholars in the universities were the ones who said, "No problem." Put a pig gene in tomato or chicken, as long as it doesn't change the appearance of the tomato or the chicken—and you can feed pig material even to a chicken and the digestive track of the chicken will purify it. As long as the chicken doesn't change too much, that is in agreement with the Talmudic position and there's no difficulty. Laurie Zoloff, an orthodox Jewish scholar at Case Western, has her research focused on the use of transgenic rice and how it could address hunger in Asian countries. When we met with lay people, their response was—and it's true for almost all traditions—abhorrence over any notion of transgenic animals, not so much over plants. It's always the case that animals are closer to us as humans so that is where we tend to identify. So you get this separation, but that has been true in the history of the religious traditions all down the centuries. Leading scholars take positions and lay people take a while to catch up and go with them. And that's true of our society in general, I would say, even for secular groups.

With reference to transgenic creations, whether animal or plant, secular vegetarians for example say that they are unnatural, whereas religious people say that you are playing God and shouldn't be meddling and creating unnatural things. And you see the power of that language in marketing, in supermarkets everywhere. "Natural" and "organic" are great sellers because they connect somewhere in the gut. It will take a while for our use of language to catch up with modern science and it will take a while within the religious traditions for the positions of the theologians to be understood and adopted by the lay people. I prefer to make my critical assessments on the basis of the scholars who have really thought through these issues, and the same with secular ethics positions.

Tom Wilson (Pennsylvania State University): Regarding an offset cap, do you think we need one? Should we just allow unlimited offsets to enter the market? Future discount rate? So how do we account for future generations who plays a large role in emission-reduction targets? Verification, validation and certification, what's that process like? Should we streamline it to allow more entries? Should we erect barriers to entry? And interaction between the new and old markets—where does the CCX[1] come in?

Benjamin Gramig: Lots of material there. I'll quickly address a couple of points and we can talk more after if you want to go into more detail. In terms of an offset cap, this is good. It's is a common element of policy proposals, an upper limit on how much of those emissions that need to be met in some binding way by the firm subject to the cap—an upper limit on how many offsets they can use. For instance, under the current legislation being debated in the United States, there is an upper limit of 2 billion metric tons from offsets, roughly 1 billion domestic and 1 billion from international sources. So there tends to be a limit—.

Wilson: Per annum?

Gramig: Per annum, that's right. Under legislation that was being debated last year, 15% of your emissions reduction obligation could be met using offsets. This is actually going to trickle down in the same way and it's going to translate into a percentage of your emissions cap for an individual power facility that can be met using those. There's a very complicated and hard-to-understand formula that actually spells out how this would happen in those 1,200 pages that were mentioned. A lot of these details are left for the implementing agencies. I don't know how this works in Canada with your government, but, when we pass legislation, oftentimes a lot of those details are left for the agencies to implement. The Environmental Protection Agency in this case, although that has changed as well in amendments to the original legislation. Agriculture has been successful in moving control of the whole offset program over to the Department of Agriculture and away from EPA. At least, as of Tuesday, that was the case. I don't know if things have changed since Tuesday. They are changing at a rapid pace.

I will address just one of the other things that you mentioned and that was discounting. How do you deal with some of these issues? The permanence issue is relevant here, in terms of how to think about how to assign these credits or allow firms to sell the offset credits they may generate from their practices. What the Chicago Climate Exchange has done, and also what is being done in Alberta, is you have to apply some sort of a discount factor to an individual practice. For instance, for every 5 metric tons I remove from the air through sequestration, I'm eligible to sell only 4. Something like that. And then access credits are commonly placed in something called a reserve pool, to cover

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[1] Chicago Climate Exchange

reversals. If people will revert on their practices to try and build up a reserve, it's a safety margin for trying to keep in touch with the cap. If you had mass reversals ,this clearly would not work. It's an imperfect solution, but it is one way they have tried to address that particular issue.

Wilson: You said the reserve pool is actually to account for a discount rate? Or those that default?

Gramig: You can think about it as default. They revert. Maybe I sign an 8-year contract and I provide sequestration for those 8 years; what happens if, at the end of 8 years, I plow up my field because I want to get another 8-year contract the following year? These kinds of details haven't been worked out, but the idea is they would then put in extra additional credits over the course of those 8 years that are there and are accounted for. Everybody feeding credits into the system is doing that so you build up a pool to try and control the total amount, or account for some amount of reversal that occurs over the whole portfolio of farmers.

Wilson: Then I guess the only other burning question is, are the new markets interacting with the old?

Gramig: They are trying to take these things into account when they design the policy. So, for instance, if you look at specifically the issue of additionality and what practices are going to be credited, all the tillage, reduced tillage, no-tillage, out there that might be eligible under the US legislation has a retroactive date. It goes back to January 1, 2002. That happens to coincide with the same rule that is in place for the CCX. It happens to coincide with the same rule that's in place for the Alberta offset system as well. So some harmonization is going on in trying to make some of these things link up, and through things like the Western Climate Initiative. There's clearly a close link in trying to develop at least the Canadian and US policies. Maybe at the provincial level right now and at a state level, but sometimes these things lead to larger initiatives and, hopefully, will provide some framework in the future. There is reference to Kyoto as well in trying to keep intact the clean development mechanism and those other linkages in the legislation, so that it leads to international efforts as well.

Audience Member: When you were discussing why economists like cap and trade, you compared, or you contrasted, CO_2 and SO_2, and suggested they were different because SO_2 delivers its problems from a point source. But something disturbs me about that because, for example, if you take the sea-level rise and the storm surge in particular coming from sea-level rise, it has much potential to impact coastal areas. Some 80% of the United States is coastal. Two thirds of the world live within 100 miles of the coastal range. So the economic cost of storm-surge-related problems is certainly comparable or more to what happened to the Appalachians.

Gramig: One of the biggest criticisms of the SO_2 program was the disproportionate division of costs and benefits. Perhaps most of the problems originate in the US Midwest where there are many old, coal-based power-generation plants, and the problems are being deposited on the northeast and the eastern part of Canada. In terms of imposing restrictions on those power plants, a lot of associated costs would be concentrated there, whereas all the benefits would be experienced by the receptors. This is clearly going to be the case where sea-level rise affects concentrated populations in various locations across the world. Concentrated costs or damages will be experienced. The emissions that occur everywhere have effects at some marginal level, right? The idea was that all these different locations contribute in an equivalent way to the overall impact on the climate.

Steve Pueppke (Michigan State University): Harold, you mentioned that religious leaders' willingness to accept GM animals and plants depended on the motivation—why they were made. On one level I understand that, but it seems to me that figuring out what the motivation is could be difficult. Would you comment on how you figure out why those things happen.

Coward: You're right. In my analysis, the most common thing that all of the religions came back to is motivation. And they all agree that the motivation has to be positive. For the good, not only of humans, but animals, plants, earth, air, water. Each tradition has its different way of trying to assess that. Buddhism uses deep meditation to come to an individual realization of what their bottom-line motivation is, doing it under a teacher. In Judaism, it's much more the law. In Christianity, it's a question of how you understand the stewardship ethic as it's laid out for you, and then are you behaving in such a way to be a steward following that ethic or are you doing it for your corporate bottom line or for your own selfish profit, and so on? So, every tradition cultures its own believers in an understanding of what selfishness would be in that tradition. Now, I think we can, even in a secular way, come to some understanding of what selfishness would be. If I followed the model that I laid out to begin with, I said if you are doing it only for yourself and your family it might be ethical, but you can't distinguish between ethical and selfish there. But if you extend it to your neighbors and everybody else in your own region and country, that could count as ethical. If you extend not being selfish to people in other countries and so on to future generations to, at the ultimate level, earth, animal, plants and water. And that can be monitored in policy decision level. What does your policy say as to how you are going to decide in your behavior? I think there are ways to put teeth into the criteria there.

PART IV–BANQUET PRESENTATION

Opportunities of the Commons: Agriculture's New Frontier

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In 1968, Garrett Hardin published an article in *Science*, "The Tragedy of the Commons," which inspired my title. Instead of talking about human beings not being thoughtful about managing resources, I want to discuss what we can do to provide ourselves with a better world for the future. We are facing major challenges. When the United States catches a cold, we in Canada catch pneumonia. We are feeling the repercussions of the current downturn in the US economy. In Saskatchewan, so far, we are doing pretty well. Although unemployment numbers aren't reassuring, I think that we will get out of this okay.

We will look at the challenges that are facing agriculture, because that's what I do for a living. I do research in food distribution. I'm a marketing professor and I teach at a business school. Also, I do research in food safety. As an industrialized country, let's look at the challenges we are facing and then I will present a scenario that I think is proper for us to believe in at this point in our history.

Agribusiness Myopia

There's a thing that I call "agribusiness myopia." Often at the WTO[1], on the world stage, nations come over with an export agenda. It's about selling corn, potatoes, hogs and cattle to the world. But we also eat and buy, so it's also about imports. Trade is about buying *and* selling, and often this myopia prevents us from believing that we are not only sellers but we are customers of commodities from around the world. In Canada we have "supply and management," a highly protectionist measure that regulates milk, poultry and eggs. We have other measures, subsidies for example, that distort trade around the world. Like the United States, we heavily subsidize our agriculture, which makes trade difficult for developing countries.

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[1] World Trade Organization.

Production is a big issue as well. We are trying to produce more and more and, thankfully, we *are* producing more, essentially because of innovations such as biotechnology. That's great, but we need to do more. Also, we need to share more of our knowledge around the world, so that other countries can grow faster and better, more economically. In Canada, the processing sector is hurting. Our labor costs are high and entire industries are being affected by trade. It's cheaper to produce in China and other places. And, of course, the processing sector is hurting. How do we add value to our commodities? Canada is known to offer great commodities to the world, but with no added value whatsoever. The United States is a little bit better than Canada in that regard, but should we do more? And how?

Water

Irrigation and water will be the number-one issue for at least the next 20 years in the prairies, and in parts of the United States as well. What are we going to do? Are we developing the technologies that will allow us to water our crops properly? Are we doing enough research in that regard? That's on the supply side—growing and producing. What about the demand? As a marketer, I care about consumers. But what about them? What is changing with consumers? First off, consumers often look for the cheap alternative. The global economic downturn is forcing consumers back to McDonald's, where some sales are up 7%. A lot of fast-food chains are doing better. Selling value-added products, premium products, is becoming more of a challenge because consumers have less money. A typical American or Canadian family spends between 10 and 12% of the annual budget on food. Thirty years ago it was between 25 and 30%. Why have things shifted? Because food is competing against plasma TVs and trips to Cancun. Food is competing against the frantic will to consume new products out there, and the food industry is suffering as a result.

How do we "brand" the food industry. How do we make food sexy again? How do we make consumers invest in food again? Over the past year, I have been happy to see food on the front page again because of the food crisis. It was reassuring. Farmers are making more money. I don't think that that is a problem. Some consumers may think it's a problem because it's costing more to buy bread and butter and produce, but, over the long term, it may be a good thing. Consumers are buying with a conscience. The 100-mile diet, anti-GMOs, vegans, organic produce, farmers' markets, the ethical treatment of animals: all of these are influencing the behavior of consumers more and more. Is the food industry adapting quickly enough to offer what consumers actually want? Markets are fragmented more than ever before. Do we fully understand what's going on? I would say that we try to, but things are moving so fast that to change the food industry—to change the psyche of price takers—will be difficult. It's a challenge.

Rural-Urban Divide

In general, consumers don't understand agriculture. Should they care? Perhaps. But when it comes to policymaking in Canada, and arguably in the United States as well, the problem is that 85% of the population lives in urban areas and they just don't understand how agriculture works. Lobbying groups are selling ideas to urbanites and urbanites are buying them. Governments are subsidizing farmers so that farmers can provide cheap food for urbanites who vote for governments. That vicious cycle has been going on almost forever, it seems, and it has affected how policymaking has evolved. It's probably nurturing the inertia over policy and over the industry. Add inflation and the credit crunch, of course, which are affecting our way of living, including the retail price of food and how consumers are buying. Here in Saskatchewan retail food prices increased by 12% in 2008. Can consumers bear that type of increase? I would argue not. Is it catch-up? Maybe it is, because for many years we were looking at increases of only 1 to 2% because we didn't want to affect poor families. Even so, 12% in a year is a lot.

Food Safety

This subject is near and dear to my heart. We saw mad-cow disease. We saw the case of Maple Leaf Foods in Canada, in 2008, which recalled over 220 products due to a listeriosis outbreak from which twenty-one died.

Food safety is becoming a huge issue. Are Canadians afraid of food? At the University of Regina we conduct frequent surveys on that subject. We are concerned. We measure fear. We measure perceptions. I can't speak for Americans, but, in general, although Canadians do trust the food-supply chain, the level of trust is being eroded. Consumers are more and more concerned. The more recalls that occur, the more consumers will ask questions. Where is the food coming from? How many kilometers did it travel? Is it safe to eat? Is it labeled correctly? People are asking more questions and holding companies accountable.

COOL Regulation

COOL regulation—country of origin labeling—in the United States, and the move to buy American products, are sources of concern in Canada. It's affecting the hog and cattle industries. What are we going to do? There is an oversupply of these products in Canada. Will we adapt? Will we change our ways? We subsidize these industries in part. Should we restructure? Should we change the architecture of these commodities as the result of these changes in policy in the United States?

Is the buy-American policy, sound and fair? I would argue that it is. I would say that Canada is not a trade-focused country. It's a trade-reliant country and that's why, when the Americans come up with a buy-American policy or a COOL policy, we are out there yelling and screaming that it's unfair. We'll go to WTO. We'll go to NAFTA[2]. And so on. Is it warranted? The world is changing quite rapidly. Is Canada changing? I would argue that the United States—regardless of what you think of how they apply policy in agriculture—has vision. You may not agree with it, but there is vision. In Canada, where is that coherent vision? We subsidize ethanol, which increases the price of corn, and then we help out farmers who can't afford to feed their hogs. It's a Band-Aid approach lacking vision. What should we do?

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[2] North American Free Trade Agreement.

The Gateway and Corridor Initiative

Population density is an issue in Canada. Logistically it's a problem. You can't move products cheaply here. Our railroads, our roads, are inefficient. All of a sudden, India and China are highly attractive markets, and we have no way to move products around. We make products quickly and efficiently, but problems in moving them have led to the Gateway and Corridor Initiative, which will allow Canada to create what I call the "St. Lawrence Seaway of the West" to move products west to Vancouver to develop markets in India and China.

Canada is falling behind. The Americans are doing better than we not only because they are better equipped but also because they have population density. They have efficient inland intermodel ports—Kansas City and Chicago, for example—which we don't have in Canada. But we are slowly figuring it out. In Regina an inland port is now being built. It's happening slowly but surely, and that is reassuring. Is it rapid enough? I don't know.

Ensuring Agriculture's Future

Let's dream a little and see what we need to do to make sure that agriculture thrives in the future avoiding boom and bust, to control our destiny and provide for our children. When prices of oil and commodities went down in the 1990s, Saskatchewan had to ask for a check from the federal government to pay salaries. How do we make sure that that doesn't happen again?

Food Prices

A steady, reasonable increase in food prices is a good thing. My chief reason is fertilizers. Food prices went up last year and look at what happened with companies like PotashCorp and Mosaic. For the first time in many years, these companies decided to invest billions of dollars in expansion projects, to increase production capacity of potash, an essential ingredient of fertilizers. They wanted to increase supply for farmers down the road. Because they were making money they could invest more and produce more. In developing countries the same applies. The problem in developing countries is that fertilizers are very expensive but, if you increase the supply, in time you will likely provide them at affordable prices. Developing countries dearly need sound agricultural policies so that they can create wealth for themselves. If these countries do well we are likely to do well also. Over the long-term, 20 to 30 years from now, prices at retail should stabilize. Not only for Canada, but for many countries around the world and we may not see repetition of the tortilla riots in Mexico in 2008. We may not see people being killed in riots all over the place because commodity prices increased by 70 to 80%. We live in volatile times, and we need to create mechanisms that allow humanity to absorb these shocks. We don't have that right now and are at the mercy of many uncontrollable variables.

Energy

Another important issue is ethanol. Is it good or bad? As far as I'm concerned, it has promise. As in the United States, we can't keep our children in rural communities. Ethanol projects are creating jobs in rural areas, so we have to give ethanol a chance. However, to rely solely on a corn-based ethanol would be a mistake. We must look at other possibilities like cellulose-based ethanol down the road, so that we don't affect food prices over the long term.

Technology Innovation

I am a big believer in biotechnology. It will play a significant role, not only for Canada but globally. It makes me sad when I see reports from various groups that biotechnology is a threat to humankind, that it's the genocide of the twenty-first century, *etc*. We have to give biotechnology a chance to prove itself over the long term. However, we need to be careful. We need to continue our research and assess risks properly as we progress.

Protectionism

We need fewer protectionist policies. I don't think that countries are trading enough. Because of the economic downturn, countries are trading less, partly because of protectionism. It's difficult for a government to provide billions of dollars for the domestic economy and also justify trade to buy products from elsewhere. That's a challenge. But we went through a depression in the 1920s and 1930s because of protectionism. We can't fall into that trap again. We need to focus more on trade—trading commodities, trading knowledge, trading technologies, *etc*—and fewer subsidies. Subsidies distort trade. They deny developing countries equal opportunities. Some great countries are progressing, like Brazil, India and Ukraine. We need to provide them opportunities to develop.

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Dr. Charlebois's research interests include food distribution and safety and his work has been widely published in peer-reviewed journals. He has written two books on agricultural policy and marketing, and he conducts policy analyses, evaluation, and demonstration projects for government agencies and major foundations, focusing on ag policy and community development in Canada and development settings. He has authored reports published by the CD Howe Institute and the Montreal Economic Institute and is a faculty research fellow for Viterra and an associate researcher for the Montreal Economic Institute.

PART V—THE STUDENT VOICE AT NABC 21

Student Voice Report[1]

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This conference's attendance by the members of the private and public sectors, researchers and professors, and students and professionals, exemplified the importance of collaboration amongst disciplines to solving problems related to climate change. It was inspiring to see so many heads together in discussion, and, as students, we had the opportunity to share our ideas.

We offer feedback from our various areas of expertise, as follows.

PLANT SCIENCE

Plant breeders go between biotechnologists and the needs of growers and consumers. As such, breeders can define technologies that are most needed. This responsibility can be

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[1] To increase graduate-student participation at NABC conferences, the *Student Voice at NABC* program was launched ahead of NABC 19. Feedback from those involved was positive, therefore the program was continued for NABC 20 and 21. Grants of up to $750 are offered to graduate students at NABC-member institutions (one per non-host institution) to assist with travel and lodging expenses. Registration fees are waived for the grant winners.

Student Voice delegates are expected to attend all of the plenary sessions as well as the breakout workshops then to meet as a group to identify current and emerging issues relevant to the conference subject matter.

Information on the *Student Voice at NABC 22* will be available in due course at http://nabc.cals.cornell.edu/studentvoice/.

[2] This report on the NABC-21 *Student Voice* discussions was provided by Ms. Sullivan.

met by the "21st-century plant breeder": a plant scientist who is focused on breeding, but who also has the capacity to help develop plant biotechnologies. Grouping breeders with biotechnologists can serve to combat the narrowed focus caused by specialization. Tunnel vision from specialization can be combated through grants that encourage collaboration between biotechnologists and plant breeders.

Plant biotechnologies are not all-encompassing solutions to the problems of adaptation and mitigation of climate change. Instead, many have optimal specific applications. We appreciate this reality and agree that new technologies must be quantitatively evaluated to find their optimal application. This is another responsibility that can be filled by a "21st century plant breeder."

From social and ethical standpoints, maintaining a natural appearance in modified organisms must be acknowledged as a public value. Public education is central to the development of biotechnologies. Communicating how biotechnologies can meet human needs will foster public interest and help remove misconceptions about biotechnology.

Education

Climate change should become a top issue discussed in the classroom, and educators and members of the scientific community need to advocate its inclusion in course curricula. Proper public discourse on climate change requires education on this increasingly important scientific theory. Courses that expose the student to the biotechnology industry, plant breeding, and product development would convey how combining these sectors may contribute to solutions. Future researchers in plant biotechnology must learn how techniques and disciplines can be combined to address climate change from various angles. In addition to scientific approaches to achieving adaptation to, and mitigation of, climate change, lifestyle and behavioral changes, such as responsible consumer choices and sustainable management practices, should be highlighted. If taken early, courses on this subject matter would enable students to place their knowledge in context.

Climate Modeling

Uncertainty causes misinterpretation of climate data, which can confuse and misdirect policymakers. Increased resolution in climate forecasting will help determine biotechnological approaches and performance targets. Accurate models are also imperative in developing appropriate risk-assessment strategies. With a better understanding of future meteorological changes, we can create better risk-management products and insurance plans to protect producers. In addition to changing temperatures, models for future crop zones must take into account growing conditions including water availability, topography, and expected changes in biogeoclimatic zones.

Soil Science

Within the climate-change debate, it is important to view soils as more than a sink for carbon; soils are the basis upon which all biotechnology and plant breeding are possible. To this end, we need to think not only of replacing nutrients removed, but also of conserving soil as a resource and reducing its loss by instituting sustainable management practices.

Efficient use of energy and nutrients go hand-in-hand in combating the effects of climate change; if we focus on nitrogen, carbon will follow. The energy currently needed to create chemical fertilizers is unacceptable, and innovative techniques, based on traditional knowledge for returning organic matter to the soil, need to be adopted.

What potent and affordable practical adjustments can be implemented by farmers? What effects will climate change have on soil microbial communities that are the drivers of nutrient cycling? With increased temperatures and increased microbial activity, what will be the effect on decomposition rates, carbon sequestration and soil fertility? These unanswered questions arose from discussions, reflecting the need for systems approaches for problem solving.

Economics and Policy

As with any public good, it falls to the government to specify the allocation of resources to environmental issues. However, despite their pivotal role, policymakers are often not well-versed in the scientific theory underlying policy formulation. Therefore, scientists, both natural and social, must reach out to policymakers to ensure that they are well informed. By working together, including with consumers, we will create more meaningful policies that benefit the public.

In the climate-change debate, the policy levers most often considered are an emissions tax and a marketable permit system, *i.e.* cap and trade. Each of these mechanisms functions as a price signal to the consumer designed to account for market failures, or externalities. Only through price signals can we hope to change human behavior as a whole. Further, it is essential that the policy mechanism allows for offsets to be provided by industries “outside the cap” to reduce emissions at lower cost.

In the agricultural sector, substantial opportunities exist to increase levels of soil-sequestered carbon and reduce N_2O emissions by improving agricultural practices. Climate-change policy has the potential to promote environmental, social, and economic contributions to society by offering offset payments to farmers who employ these practices. This would introduce a newly shaped form of agricultural subsidy or financial stimulus for using more environmentally responsible farming practices. However, many of these ideas mean new costs, new practices, and new risks for the farmer; policymakers should consider solutions that spread both the benefits and risks of new practices to all stakeholders. Also, soil carbon is impacted by small fluctuations in temperature and moisture, and a large degree of uncertainty surrounds the measurement of N_2O emissions. If the offset market is to include agricultural carbon, it is important that we carefully monitor and regularly document emissions reductions.

Conclusion

Fundamentally, climate change, food security, and, by extension, global stability, hinge upon the ability of the human race to support itself in a sustainable fashion. This will be facilitated by the collaboration of economists and social and natural scientists in a manner that focuses on solutions that are applicable to society. Agriculture is a perfect reflection of society’s approach to caring for itself; it is the act of humans cultivating the

Earth upon which we depend. It is clear that agriculture is already, and will continue to be, affected by climate change. With a systems approach we can create life-cycle analyses to fully assess the roles of various disciplines in achieving adaptation to, and mitigation of, climate change.

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Index

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