

Climate change and the Canadian agricultural environment



Edited by
Jerry A. Ivany and Robert E. Blackshaw

Canadian Weed Science Society
Société canadienne de malherbologie



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(ISBN 978-0-9688970-8-9)
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Citation for Volume:

Ivany, J. A. and R. E. Blackshaw, eds. 2012. Climate Change and the Canadian Agricultural Environment. Topics in Canadian Weed Science, Volume 8. Pinawa, Manitoba: Canadian Weed Science Society – Société canadienne de malherbologie. 87pp.

Citation for Chapter:

Author(s). 2012. *Title*. Pages xx-xx in J. A. Ivany and R. E. Blackshaw, eds. Climate Change and the Canadian Agricultural Environment. Topics in Canadian Weed Science, Volume 8. Pinawa, Manitoba, Canadian Weed Science Society – Société canadienne de malherbologie.

Printed in Canada

Preface

The Canadian Weed Science Society – Société canadienne de malherbologie (CWSS-SCM) is pleased to present “Climate change and the Canadian agricultural environment”, the 8th volume of Topics in Canadian Weed Science. This volume is a compilation of peer-reviewed papers that were presented during the plenary session at the 2009 CWSS-SCM annual meeting held in Charlottetown, Prince Edward Island.

Topics in Canadian Weed Science is intended to advance the knowledge of weed science and increase awareness of the consequences of weeds in agroecosystems, forestry, and natural habitats. The volumes cover a wide range of topics and provide a diverse source of information for weed science professionals and the general public.

The plenary session topics at the CWSS-SCM annual meeting are of both national and international interest, and we invite weed science professionals to attend our annual meetings. The annual meeting is usually held in late November, with locations alternating between Eastern and Western Canada. Meeting details are available on the CWSS-SCM website (www.weedscience.ca).

The CWSS-SCM Board of Directors expresses their gratitude to J. Ivany and R. Blackshaw (editors), the Charlottetown Local Arrangements Committee, the contributing authors, and the reviewers who have made this publication possible. Other volumes of Topics in Canadian Weed Science include:

- Vol. 1: Field boundary habitats: Implications for seed, insect, and disease management;
- Vol. 2: Weed management in transition;
- Vol. 3: Soil residual herbicides: Science and management;
- Vol. 4: The first decade of herbicide-resistant crops in Canada;
- Vol. 5: Invasive plants: Inventories, strategies, and action;
- Vol. 6: Physical weed control: progress and challenges; and
- Vol. 7: The politics of weeds.

Most of these volumes are available for purchase and can be ordered through the CWSS-SCM website (www.weedscience.ca).

Stephen Darbyshire
Publications Director
CWSS-SCM

Acknowledgements

Cover

Photograph: Funnel cloud over Scott Research Farm in Saskatchewan by Eric Johnson.

Cover Design for the Series: Ralph Underwood, Agriculture and Agri-Food Canada, Saskatoon Research Centre, Saskatoon, SK.

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The editors would like to thank the reviewers for their assistance in reviewing the papers contained in this volume: David Clements, Robert Gulden and Lloyd Dossdall.

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SYMPOSIUM

Climate Change and the Canadian Agricultural Environment

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The papers in this volume of Topics in Canadian Weed Science were presented at a symposium held during the Canadian Weed Science Society - Société canadienne de malherbologie (CWSS-SCM) meeting in Charlottetown, Prince Edward Island in November 2009. The topic of “Climate Change and the Canadian Agricultural Environment” was chosen as the symposium theme because across Canada the effects of climate change are being seen as the decades pass. Weed scientists, who conduct periodic weed surveys, have noted the spread of several noxious and invasive species into areas where they were not noticed previously and farmers sometimes have difficulty achieving control in different agricultural situations. Crops that were not previously grown in some parts of Canada are now productive and adding greatly to local crop rotation options. Part of this change could be attributed to improved genetics and breeding of cultivars for cooler climates but some may be due to climate change. Although some research has been done in Canada, the potential and profound effects of climate change as it impacts weeds has not been given the level of research required to allow producers to prepare and adapt. How we control weeds and plant pathogens in crops, the impact of changes on crop management can all exert demands for new weed science technologies.

In this symposium, we asked our speakers to discuss the evidence of changes due to climate change and the challenges in weed science that will have to be met. They have presented the evidence for climate change, viewpoints about climate change and potential effects in Atlantic Canada as well as recent studies on changes in weed, disease and insect distribution in crops in western Canada. The studies are some of the earliest conducted in agriculture in Canada and emphasize the need to have more research conducted on basic principles to improve our understanding of mechanisms involved and possible ways to solve problems that may arise.

Climate change and the impact on the future of agriculture

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Monsanto, a company wholly dedicated to agriculture and a leading global provider of agricultural technology, recently called upon its Fellows to report on the science behind climate change and its likely impact on agriculture. The Monsanto Fellows Climate Change Panel found that although the exact magnitude of current and likely future human influences on climate is uncertain, several key facts about climate and the future of agriculture are known. Convincing data show that temperatures are increasing, and that changing precipitation patterns are already affecting agriculture. Impacts on crop production are likely to intensify, but not in a uniform manner, either spatially or temporally. Some regions, such as Africa, Australia, and certain portions of Europe, are projected to be quite negatively impacted, while other important agricultural production areas, such as Argentina and temperate portions of North America, may actually benefit from the expected changes, at least initially (over the next few decades). However, most models suggest that all regions are projected to suffer productivity declines by the end of the 21st century, unless successful mitigation measures are implemented soon. Exacerbating the climate change challenge, demographic and economic trends suggest that a doubling of overall crop productivity will be required by mid-century, in order to meet the food, feed, fuel, and fibre demands of an estimated world population of 9 billion by the year 2050. Clearly, new technologies are needed for agriculture to supply this escalating demand, while at the same time adapting to a changing climate and hopefully even contributing to climate mitigation, by reducing greenhouse gas emissions associated with crop production. Fortunately, good progress is already being made. For most crops of global importance, there is considerable buffering and redundancy in breeding, seed manufacturing, and research sites, which should enable us to keep pace with the expected rate of changes. Crop chemical manufacturing is managing its “carbon footprint,” and there are new biotechnology-based crop traits in the research pipeline, such as drought tolerance and nitrogen-use efficiency, that will help in both mitigating and adapting to climate change.

Additional keywords: global warming, drought, climate change mitigation, carbon footprint

Introduction

Agriculture is the world's oldest industry, and climate change is its newest challenge. Despite the antiquity and existential necessity of agriculture, it nevertheless now finds itself embroiled in several contemporary controversies over its widespread use of technology to meet accelerating demands for food, feed, fibre, and fuel. The Green Revolution, powered by the widespread adoption of inorganic nitrogen fertilizers, is claimed by some to be causing undesirable environmental effects as it enables rapid population growth and even more demand (Hazell 2002). This technology-driven cycle of accelerating crop production is feared by some to be unsustainable, as the consumption of finite resources and the negative impacts of intensified crop production conspire to squeeze the ability of farmers to meet demand, in a kind of neo-Malthusian vortex (Dyson 2001). For example, the widespread use of inorganic nitrogen fertilizers results in significant greenhouse gas (GHG) emissions, thereby potentially contributing to the very heat and moisture stresses that may already be limiting the productivity of cropping systems (Stein and Yung 2003). Such concerns have caused some to express serious doubts about the long-term sustainability of modern agricultural techniques (Stewart et al. 2002).

But agriculture has never been easy. Weed control, in particular, has plagued agriculture from its onset. Indeed, the first few pages of the Bible describe this problem as a direct consequence of mankind's disobedience: "cursed is the ground because of you ... both thorns and thistles it shall grow for you." In addition to unwanted weedy plants, there are numerous insect and fungal pests that plague farmers. But now, according to many environmental scientists, an even larger threat of Biblical or even Apocalyptic proportions looms over agriculture – global climate change (Gore 2006; Hansen et al. 2008; Weart 2003).

The question of whether mankind's increasing combustion of fossil fuels is inducing climate change has become a contentious and seemingly intractable geopolitical issue. Though it seems to have been accepted by much of the climate modeling community (Anderegg et al. 2010), a vocal minority of scientists hold to a firmly contrary view, for instance, Richard Lindzen (MIT) and Roy Spencer (ret. NASA). These actually lop-sided scientific debates have been selectively amplified in the popular media, in a manner that has created what seems to many to be an evenly divided body of squabbling scientists. This has largely confused both the lay public and policymakers, helping to stifle all attempts at a concerted global political approach to limiting GHG emissions (Gore 2006).

It was amidst this backdrop in late 2006 that the Board of Directors for Monsanto, a company wholly dedicated to agriculture, called upon its leading scientists to report on the science behind climate change and the extent of the threat to agriculture. Monsanto's Technology organization (led by Dr. Robert Fraley) accomplished this task by calling for volunteers from among its Fellows, who formed the Monsanto Fellows Climate Change Panel, which prepared the report. This paper summarizes that report and the conclusions that were presented to the Monsanto Board in June 2007. As this current summary is actually being prepared

in July 2010, some of the data have been updated to include more recent information.

Methodology

The Monsanto Fellows Climate Change Panel was staffed largely by volunteers from among Monsanto's Fellows. Monsanto established its Fellow Program in 1948 in order to recognize, utilize, and develop its scientists and their scientific leadership skills. It includes a rigorous nomination process, oral reviews every three years, and claims one Nobel Prize winner (Chemistry, 2001) from among its ranks: Dr. William S. Knowles, who was recognized for his seminal work on chiral synthesis. There are now about 100 Fellows, representing less than 5% of the company's scientists. Twenty-one of them answered the call for volunteers issued in December 2006. The Panel was facilitated by Monsanto's Dr. David Butruille and was overseen by a three-person Steering Team: Dr. Fraley, Dr. Robert Reiter, and Dr. David Fischhoff. The Panel itself was organized around six theme areas, each led by one of the Monsanto Fellow volunteers:

Dr. Gregg Bogosian	Global and regional change and seasonal forecasting
Dr. Gerry Dill	Biological changes
Dr. Mike Edgerton	Reduction of carbon emission
Dr. David Gustafson	Evolution of risk
Dr. Mike Hall	Carbon sequestration
Dr. Ty Vaughn	Brainstorming

The six theme teams operated largely autonomously, but each of the Fellow volunteers served on two of the theme teams, which, in addition to regular contact with the Steering Team, fostered good communication exchange. Because this area of science was largely new to Monsanto, the work of the Panel necessitated interaction with a number of Consultants, who visited St. Louis for a one-day internal Climate Change Symposium on March 3, 2007. The Consultants were:

- Dr. Barry Goodwin, North Carolina State University
- Dr. Steve Long, University of Illinois
- Dr. Donald Ort, University of Illinois
- Dr. Nicholas Piggott, North Carolina State University
- Dr. Cynthia Rosenzweig, Columbia University
- Dr. Steve Schneider, Stanford University
- Dr. Mark Taylor, Sandia National Labs
- Thomas Zacharias, National Crop Insurance Services

On May 2, 2007, an internal meeting was held among all Panel members and two additional consultants: Dr. Andrew Leakey (University of Illinois) and Dr. Ralph Quatrano (Washington University). This internal meeting was used to share

findings from among the six theme teams and develop a consensus on the final report to the Board.

Findings

The Panel collected extensive information on the development of modern climate science, and the origins of the theory of man-made global warming. While it was not asked – nor did it take – an explicit position on the accuracy of that theory, the Panel found unequivocal and convincing data that temperatures are now increasing, in a manner largely consistent with the theory, and that changing precipitation patterns are already affecting agriculture. However, the Panel found that the impacts of climate change would be highly regional in nature, as detailed further below. Crop yields in certain areas are likely to benefit from the predicted changes through mid 21st century, but productivity is expected to be hampered in all regions by the end of the century, unless mitigation occurs. The Panel found that modern agriculture is well positioned to deal with the expected pace of climate change, and has significant untapped potential to contribute to reduction of GHG emissions. Further details on each of these findings are presented below.

Development of modern climate science

This brief history of the development of modern climate science is drawn primarily on material presented in an excellent book by Stephen Weart, *The Discovery of Global Warming* (2003). According to Weart's studies, the possibility that climate might be affected by man-made GHG emissions, particularly those related to the combustion of coal and other fossil fuels, appears to have first been proposed in 1896 by Svante Arrhenius, a Swedish scientist, whose name should be recognizable to both biologists and chemists for the chemical reaction rate plotting method that bears his name (natural logarithm of the rate constant vs. the inverse of the absolute temperature). Another Swede, Arvid Högbom, refined Arrhenius' calculations. The numbers Högbom derived for the impact of doubling atmospheric CO₂ on global temperatures were in the range of 10°F, a bit higher than most of the values accepted today. However, given the rather low amounts of fossil fuel burning at that time, neither Arrhenius nor Högbom was particularly alarmed by the results, and a little warming sounded nice in Sweden anyhow. But the main reason for their lack of concern was that they incorrectly assumed it would take many millennia for human activities to double the amount of carbon dioxide in the air. This now appears to be a level that will be reached by about the year 2060, without some form of global regulatory intervention.

Subsequent scientific scrutiny of Arrhenius's and Högbom's calculations brought a large degree of scepticism in the early twentieth century. This sceptical attitude continued until 1938 when another scientist, Guy Stewart Callendar, announced a more detailed restatement of the basic theory. As with Arrhenius, a fellow northern European, Callendar believed that a little warming would be a good thing, perhaps even helping agriculture. And, just like Arrhenius, he incorrectly

prognosticated a very gradual increase due to his assumption of a very slight rise in atmospheric carbon dioxide, and too weak of a dependence of global mean temperature on this parameter. But his calculations were largely ignored or dismissed, just as the previous work of Arrhenius and Högbom had been.

It was also during the 1930s that a Serbian engineer, Milutin Milankovitch, carried out excessively difficult and tedious calculations involving slight variations in the Earth's orbit, which he proposed as an explanation for a key feature of the Ice Age: the cyclical periods of glaciation in the "recent" (<1 million year) history of the Earth's climate. The changes he calculated in the tilt of the Earth's axis and the shape of its orbit were incredibly small. Such slight perturbations would only be capable of causing dramatic shifts in the Earth's climate if the planetary weather system was intrinsically "metastable"—capable of slipping into either a much colder or a much warmer condition. Increasingly, climate scientists came to believe this was possible. As a physical mechanism for how this might happen, they proposed the existence of so-called "positive feedback" which could cause warming to accelerate. For example, as snow and ice melt, they allow the underlying soil or open water to absorb much more incoming sunlight, further accelerating the rate of melting. Indeed, many such feedback processes have found their way into the modern climate simulation tools that are used today. Scientists began to accept the idea that rapid changes in the Earth's climate had taken place in the past and were possible in the future.

The next major advance came through a number of scientists (Keeling and Whorf 2004), who collaborated on the collection of the first accurate data on atmospheric carbon dioxide levels in Antarctica and at Mauna Loa, Hawaii (both far enough removed from local carbon dioxide sources to collect globally-representative information). The Mauna Loa data (see Figure 1) tell a compelling story about the rate at which the atmospheric carbon dioxide level continues to climb. The annual fluctuations are caused by vegetation in the Northern Hemisphere, which consumes carbon dioxide during summer months and then releases it during the winter months of decay.

Another key technology advance came at about the same time from Cesare Emiliani, a geology student from Italy working at the University of Chicago, who worked out many of the experimental details in a new isotopic method for inferring prehistoric temperatures, based on the presence of a rare nuclear isotope of oxygen, ^{18}O . In 1947, the nuclear chemist Harold Urey had discovered that the ratio of ^{18}O in the shells of a class of marine organisms (*foraminifera*) was directly related to the temperature of the water at the time that the organism had lived. Since these shells can be found at the bottom of the ocean in discrete layers that may be simply counted and dated, the past temperature of the Earth's oceans could be directly determined. Once the technical details were worked out, climate scientists had a much better record of historical temperatures with which to test various models of the ice ages and of the climate's true sensitivity to the small variations in sunlight

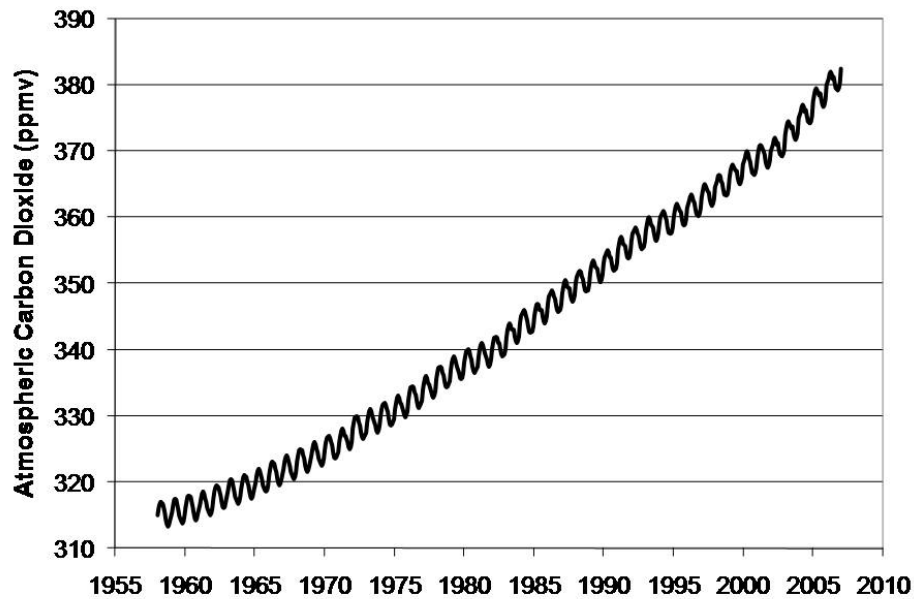


Figure 1. Carbon dioxide levels in the atmosphere, as measured at Mauna Loa (source: Keeling and Whorf 2004).

suggested by Milankovitch's calculations. A series of debates then ensued within the climate science community on whether the Earth's climate was really as sensitive to small perturbations as the increasing body of evidence was suggesting. This concept is still being debated, and is partly responsible for the scepticism about the global warming theory in the scientific community today.

The next big advance in climate science was the computer, first analog, then digital, then the supercomputers of today. But scientists have been continually stymied when they try to model the weather, no matter how powerful their computers have become. We continue to be aware of this limitation in our personal lives today. Forecasts for anything more than about 48 hours out are notoriously inaccurate. It turns out that the inability to predict the weather is not because our computers are not fast enough, or that we have the math all wrong. It has to do with the coupled systems of nonlinear differential equations that govern the system. It turns out that such systems defy reliable prediction, as first explained in detail in 1961 by Edward Lorenz (the so-called "Butterfly Effect"). Tiny changes in the initial values for such systems unavoidably cause chaotic results within just a few time steps of the computer simulation. But the Butterfly Effect is not just a technical flaw in the computer programs – it is essential aspect of the weather. Lorenz mathematically proved that such nonlinear systems have this intrinsically chaotic behaviour (Gleick 1988). So there is a built-in limitation to the ability of any computer model, no matter how powerful or sophisticated, to accurately predict the weather.

Acceptance of Lorenz's proof of the existence of such "chaotic systems" helped shape the thinking of modern climate scientists that relatively rapid changes in the earth's climate were possible. But it also presents an apparent discrepancy for those who also claim that modern global climate models can accurately forecast future climate. It turns out that no discrepancy, in fact, exists. Climate represents the long-term trend in weather, rather than the daily fluctuations that we call "weather." These long-term trends represent a different class of differential equations, so-called Boundary Value problems, rather than the Initial Value problems that are subject to Lorenz's Butterfly Effect. Thus it turns out that reasonably accurate climate forecasts should be possible, once we have good models and good input data.

From the mid-1960s into the early 1970s, climate science became engrossed in unravelling a new puzzle that has ended up hurting its credibility in the eyes of the public and has also made it easier for sceptics to poke apparent holes in the current chorus of global warming warnings. The key question was this: was there a danger that man-made pollution could cause drastic cooling due to the continued release of aerosols, particulate matter, and even contrails produced by jet travel? The question received additional attention when researchers found compelling evidence that the Earth was somewhat "overdue" for its next period of heavy glaciation, at least according to the time series of temperature records that were emerging from ice core records (see Figure 2). In 1972, these data helped prompt

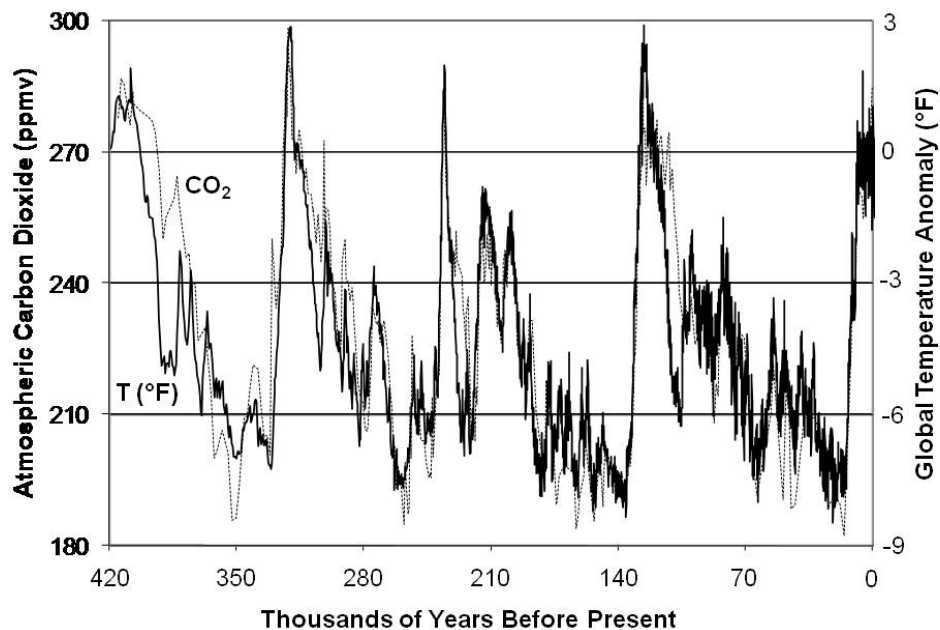


Figure 2. Global mean temperatures and carbon dioxide levels for the past 420 thousand years, based on the analysis of air bubbles trapped in ice cores collected on Antarctica (source: Vostok ice cores).

the leading glacial-epoch experts to meet at Brown University and to conclude, “the natural end of the warm epoch is undoubtedly near.” There were several naysayers at the conference, but the majority succeeded in issuing a statement saying that serious cooling “must be expected with the next few millennia or even centuries.” This press release and the hullabaloo that followed managed to make it to the front page of *Time Magazine* that year and even prompted a letter of warning to Richard Nixon.

At the time of these cooling warnings, some scientists were instead already concerned with the possibility of global warming from man-made carbon dioxide in the atmosphere, but the majority view at that time was that global cooling was the greater danger, due to the man-made addition of aerosols and particulate matter into the atmosphere (sometimes known as “global dimming”). Looking back at the temperature record for that period now, it seems hard to fault the consensus view. The current spate of warming began in around 1970, and the data for the previous thirty years had showed steady cooling.

During the 1970s, the question of rising carbon dioxide levels in the Earth’s own current atmosphere would occasionally still come up, based largely on the vocal advocacy of Schneider and others. But it received little traction in either the larger scientific community or the public, since there was still no convincing evidence of a global warming trend at that time. Schneider and a colleague published an apparently prophetic paper during this period, suggesting that warming due to higher carbon dioxide levels would soon begin to dominate the Earth’s climate after 1980. A 1977 National Academy of Sciences panel issued a report also suggesting that catastrophic warming, not cooling, was the greatest threat to the Earth’s climate. But this all came too soon after the 1972 Brown University group’s warnings of an imminent ice age to win very many converts. At the end of the decade a World Climate Conference was held in Geneva in 1979, convening 300 experts from 50 countries. They issued a consensus statement recognizing the “clear possibility” that an increase in carbon dioxide “may result in significant and possibly major long-term changes of the global-scale climate.”

The 1980s saw the development of the first true Global Climate Models (GCMs) by independent teams of researchers from around the world. Among the key advances in the development of these models were the addition of a true oceanic circulation model, representation of land topography, and several feedback processes, such as the melting of snow or ice mentioned previously. Positive feedback processes have the potential to greatly accelerate the rate of warming. On the other hand, negative feedback would tend to retard warming and act more like a thermostat to keep temperatures where they are. A simple example of this is cloud formation. As the ocean warms, more water evaporates, but this increased atmospheric water content could increase cloud cover, which would tend to reflect more sunlight back out to space, thereby slowing the rate of warming.

James Hansen, a scientist with NASA, has argued for strong positive feedback, based on his analysis of climate over the past 65 million years (Hansen et al. 2008). A re-plotting of both Hansen’s paleoclimatic data and more recent data as a “phase-space” diagram is shown in Figure 3, with global mean temperatures as a

function of the direct radiative forcing caused by atmospheric carbon dioxide. These results are consistent with strong positive feedback, and also show that temperatures far higher than those observed at present are possible in the earth's climate system. The fact that the recent temperature trajectory has still not "caught up" with the warmer temperatures of the past is a function of the slowness with which air temperatures have been able to respond to the relatively rapid (in geologic terms) shock to the earth's energy balance caused by the rapid increase in CO_2 . But the graph clearly implies that much warmer temperatures are inevitable. On the basis of analyses such as these, Hansen has asserted that 350 ppm should be the highest tolerable concentration for atmospheric carbon dioxide. As shown previously in Figure 1, the current concentration is nearly 390 ppm, with no sign of a decrease in sight.

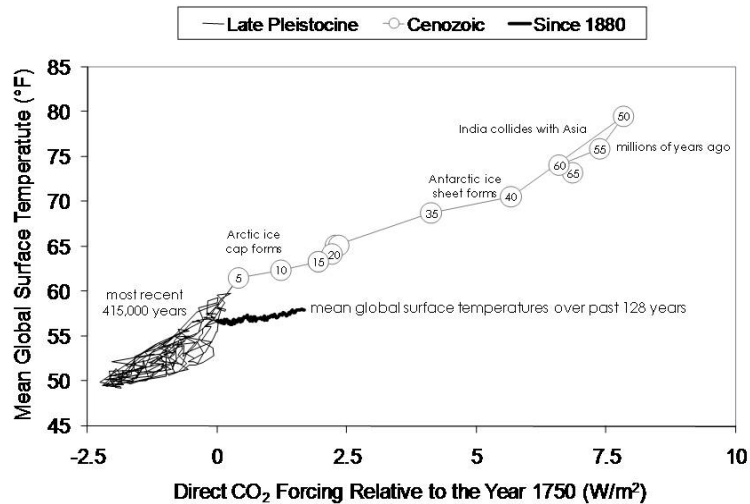


Figure 3. Phase-space diagram of global mean temperatures as a function of the direct forcing of carbon dioxide (sources: replot of data from NCDC, Vostok ice cores, and Hansen et al. 2008)

By the mid-1980s political pressure began to grow, first in Europe and eventually in the United States, for "something to be done" about the global warming issue. Although he failed to win the nomination, Al Gore was a leading presidential candidate on the Democratic side, and he made concerns over global warming one of his key issues during his 1988 campaign. The first "tipping point" came during that hot summer of 1988, when much of the Midwestern United States was suffering a prolonged drought and an unusually hot summer. Responding to all of these pressures, the United States finally relinquished its veto power and the United Nations created the Intergovernmental Panel on Climate Change (IPCC), which now continues to lead the world efforts in this area, with a considerable amount of funding and political clout. Many of today's leading climate scientists chose to join the IPCC, which has since issued a series of four detailed assessment reports: most recently in 2007 (IPCC 2007a, 2007b).

The most recent IPCC report reflects considerable progress based on large amounts of new and much more comprehensive data, improvements in the understanding of the underlying processes, and more sophisticated analyses of the model results. All of these factors enable better characterization of the uncertainties in climate predictions. The report quantifies the relative impacts of man-made and natural factors in terms of “net radiative forcing” in units of energy per unit area (watts per square meter). According to the IPCC, the most important factors include changes in the abundance of greenhouse gases, particularly carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (CFCs). They conclude that the changes brought on by the increasing concentrations of these gases have a significantly greater effect than the other factors, such as man-made ozone, albedo (surface reflectivity) effects, aerosols (direct and indirect via cloud formation), and variations in solar activity. Of all the other factors affecting climate, the IPCC scientists currently believe that the largest cooling factor is the presence of man-made aerosols in the atmosphere, which are just enough to offset all of the warming factors except for carbon dioxide, which ends up driving the overall global system in the direction of warming.

The 2007 IPCC report is the first from the panel to discuss a very troubling and recently discovered man-made impact on the sea: ocean acidification (Caldeira and Wickett 2003). New data show that at least half the carbon dioxide produced by man has been absorbed by the oceans, and this has already dropped its pH by 0.1 units, which corresponds to a 30% increase in the concentration of hydrogen ions. As the pH drops and acidification continues, the solubility of calcium carbonate, the chemical that forms the shells of many marine organisms, will increase. The species at risk include coral, molluscs, and a number of microscopic organisms.

Warming is now accelerating

The Panel found convincing evidence that global temperatures are increasing, consistent with the basic tenets behind the theory of man-made global warming (IPCC 2007a). All temperature records, whether based on ground or satellite observations, agree that warming has been steadily accelerating since the late 1960's (NCDC 2010; Smith and Reynolds 2004; Smith et al. 2005; United States Climate Change Science Program 2008), especially on the land surfaces of the Northern Hemisphere, where most of the world's crop production takes place (Figure 4).

A seven-year moving average (centered) has been added to Figure 4, in order to see the overall trend a little more easily. The striking thing is that the temperature trend has been accelerating in a continuous manner for the past forty years. Why has this very strong warming signal suddenly appeared in the record? A variety of possible explanations could be offered, but it seems likely to be a result of the carbon dioxide warming effect finally becoming dominant over the mix of other man-made activities that have a net cooling effect, especially conventional air pollution due to particulate matter. The upward curvature is also consistent with positive feedback being induced by increased evaporation of water into the atmosphere with that warming itself adding to the overall greenhouse effect.

Whatever the actual cause of the emergence of this accelerating warming curve, it is fit extremely well by the following equation, which was obtained by simple least squares regression to the seven-year moving average of the observed data from January 1968 to January 2007, when the Panel was conducting its investigations. It is a quadratic in terms of time:

$$T = [a (Y - 1968)^2] + [b (Y - 1968)] \quad [1]$$

where T is the Northern Hemisphere land surface warming relative to the year 1968 (°F),

Y is the year (conventional Gregorian calendar),

a is 0.0008338 °F/yr², and

b is 0.024337 °F/yr.

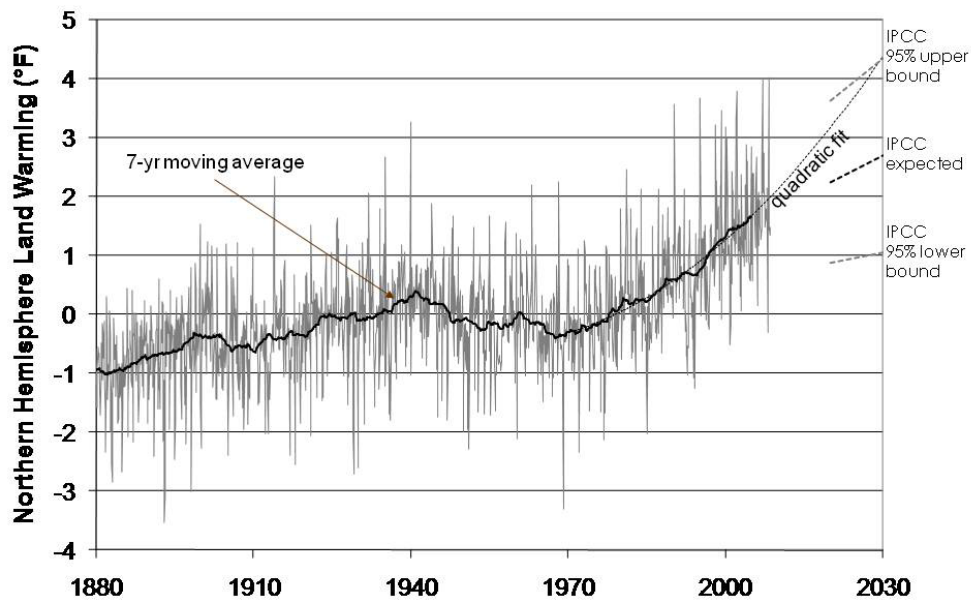


Figure 4. Observed monthly Northern Hemisphere land surface temperature anomalies (relative to the 20th century mean) are shown along with the seven-year moving average, a quadratic fit to this moving average from 1968 to the present time (Equation 1), and IPCC predictions for the warming trend in the Northern Hemisphere during the decade of the 2020s (source of observed temperatures: National Climatic Data Center <http://www.ncdc.noaa.gov/cmb-faq/anomalies.html>).

As is plainly visible in Figure 4, this quadratic fit predicts much faster warming than the IPCC model predictions for the decade of the 2020s. A closer look at how well Equation 1 fits the observed warming since 1968 is shown in Figure 5. The degree of fit is surprisingly good, and the monthly temperature

anomalies observed since it was first fit to the data (January 2007) continue to bounce around the simple quadratic fit in a satisfyingly accurate manner, as shown in the lower right of Figure 5. As shown in the upper left portion of Figure 5, if temperatures were to continue to follow this quadratic through the end of the twenty-first century, it would result in a degree of global warming that would clearly be noticeable and unacceptable (16°F by the year 2100). Of course, it is unknown whether this very intense rate of global warming will continue at such an alarming pace, but this possibility is deeply unsettling.

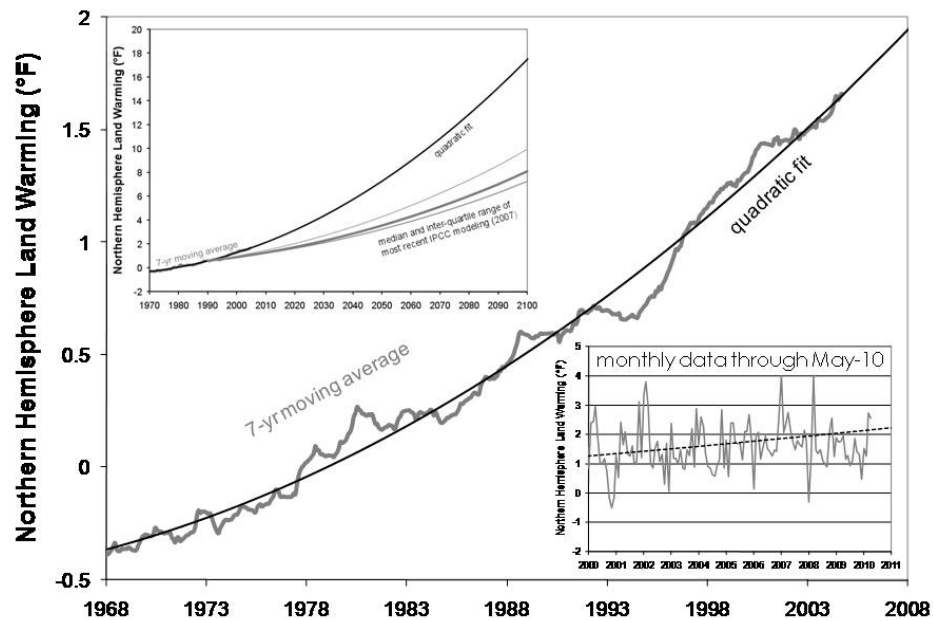


Figure 5. Seven-year moving average of observed Northern Hemisphere land surface temperature anomalies for the past forty years in comparison with the quadratic fit (Equation 1). The inset at lower right shows observed monthly anomalies through May 2010 (most current available as this went to press), in comparison to Equation 1. The inset at upper left shows the predictions for the 21st century for Equation 1 and the median of IPCC model predictions.

As for the hypothesis that man-made GHG emissions are largely responsible for the observed warming, there is considerable evidence that it is true. As shown in Figure 6, the rapidly rising concentrations of CO₂, N₂O, and CH₄ are directly attributable to the recent increases in world population. Although CO₂ is the most important of these three gases and is mainly a result of burning coal and other fossil fuels as fuel and a source of electricity, agriculture is responsible for the majority of the N₂O and CH₄ emissions. Combined with the impact of land use change (the carbon released when land is converted to crop land), agriculture is directly responsible for approximately 25% of all man-made GHGs (Burney et al. 2010).

As indicated in Figure 6, the maximum rate of world population growth occurred in the early 1960s, with a doubling period of only 32 years. Growth has slowed since that time. Various models have been proposed for world population by mid 21st century (IPCC 2001). However, it is expected to total over 9 billion, with a doubling of demand for food, due the combination of a larger population and rising global affluence (Field to Market, The Alliance for Sustainable Agriculture 2009).

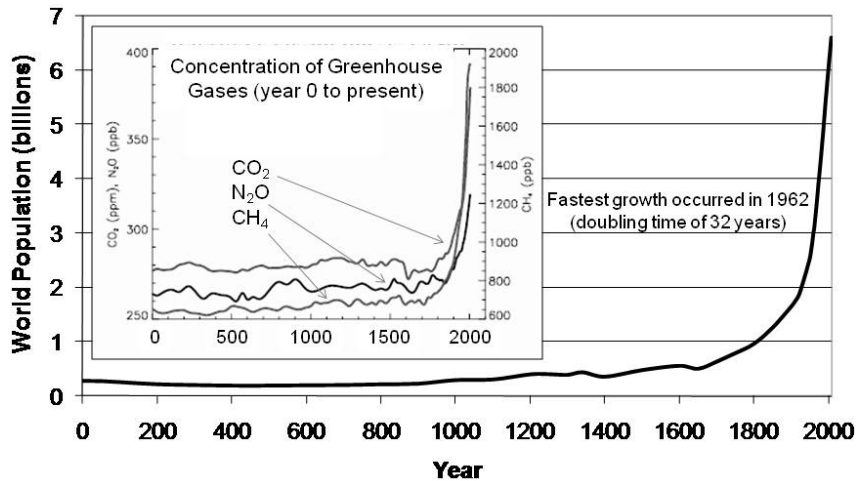


Figure 6. Median of world population estimates for the past two thousand years. The inset shows the growth of atmospheric greenhouse gases over the same period (source: United Nations for population estimates and IPCC for greenhouse gas concentrations).

The challenge to meet this increasing demand for food will be made doubly difficult by the increasing stress of man-made global warming. The three man-made GHGs highlighted in Figure 6 (CO₂, N₂O, and CH₄) are already exerting a significant warming impact. As shown in Figure 7, the cumulative impact of these gases is steadily increasing and is now nearly 3 W/m² (United States Climate Change Science Program 2008). This represents about 2% of the energy absorbed by incoming solar radiation. In other words, this is the additional warming that would be caused by moving the earth a million miles closer to the sun.

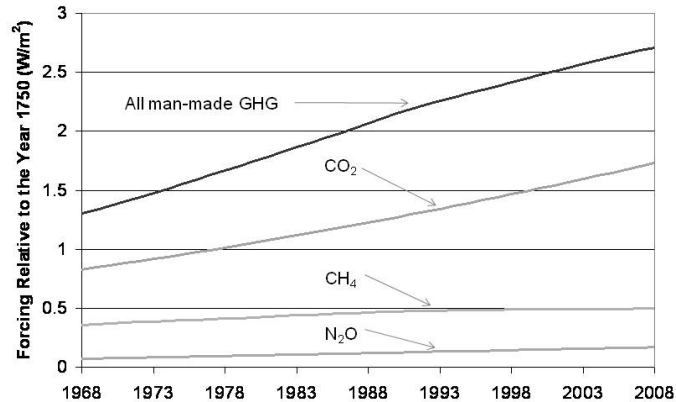


Figure 7. The steadily increasing warming impact of all man-made greenhouse gases (GHGs) and the individual contribution of the top three man-made GHGs: carbon dioxide, methane, and nitrous oxide (source: National Climatic Data Center).

Expected course of climate change

Projections of future warming are heavily dependent on the rate of continuing economic development and the degree to which subsequent generations will adopt new technologies to reduce greenhouse gas emissions (IPCC 2001). However, regardless of the particular development scenario, the pattern of global warming will be non-uniform, both in terms of temperature rise and changes in precipitation (Christiansen et al. 2007; Diffenbaugh et al. 2005; IPCC 2007a, 2007b; LeGrande et al. 2006; Seager et al. 2007). The following general statements characterize the expected pattern of future climate change.

Warming is predicted to occur mainly ...

- over land areas rather than over the oceans
- near the poles rather than in the tropics
- at night rather than during mid-day
- in winters rather than in summers

Precipitation changes are less certain, but ...

- an overall increase certain, especially near the poles
- decreases will occur in many sub-tropical areas
- current deserts are likely to expand
- more frequent extreme events are likely

Impact on agriculture

Considering all of these impacts from the perspective of agriculture, there is little doubt that water, either too much of it or too little, is the biggest threat. By the middle of the twenty-first century, average annual river runoff and water availability should increase by 10–40% in high latitudes and in typically wet tropical regions, but water will decrease by 10–30% over currently drier areas. Thus, drought-stricken areas will likely increase in spatial extent. Conversely, heavy precipitation events will increase in frequency, which are often a source of crop damage. Water availability will be severely impacted in those regions dependent on freshwater sourced by snow cover and glaciers, since both of these freshwater resources will become severely limited during the course of the 21st century.

Crop productivity is projected to increase slightly due to climatic factors at mid to high latitudes until mid-century, when the excess heat will begin to harm yield. At lower latitudes, which are dominated by developing countries of lower adaptive ability, crop yields are probably already being negatively impacted by climate factors, and this trend will worsen as the warming proceeds. Crops in all world areas are expected to be negatively impacted by changes in rainfall patterns, not only in terms of drought, but also heavy precipitation events, and the possible increased frequency of severe storms. Aquaculture and fisheries will be adversely affected due to the combination of warming, acidification, and other stressors (such as hypoxia).

In addition to the obvious effects of higher temperature and increased moisture stresses (both too much and too little rainfall), pest pressure is expected to intensify. Weeds will experience changes in their range and some will become more productive and prolific, due to the natural fertilization of higher CO₂ levels and potentially lengthened growing seasons (United States Climate Change Science Program 2008). These changes in weed populations have implications for both pathogens and the insects that utilize such hosts.

As with weeds, insect pests are expected to increase their ranges, especially toward the poles. Insects are also hosts to other organisms, including some that have both agricultural and human health implications. Plant diseases are nearly all made worse by warmer temperatures, so this represents yet another potential threat to crops. Finally, the phenomenon of resistance among all categories of pests is expected to become a greater concern, as the number of annual generations increases, especially for those regions which no longer experience wintertime temperatures cold enough to kill off potentially resistant survivors.

Drought is expected to become an increasing threat to agriculture, but it will be highly regionalized (Solomon et al. 2009). It is expected to be most intense in southern Africa, the Mediterranean, southwestern North America, eastern Brazil, western Australia, and southeast Asia. Given the importance of each of these areas to crop production, this highlights the importance of developing new crop varieties with drought tolerance, whether via biotechnology or advanced breeding techniques.

Fortunately, there is strong evidence that recent advances in agricultural technology are keeping pace with the rate of climate change, with strong potential

for continued adaptation to warmer temperatures and even mitigation of GHG emissions (Burney et al. 2010; Pielke et al. 2007). The primary mitigating effect of modern agricultural technology is its potential to boost crop yield, which Burney and co-authors found has resulted in the avoidance of a vast sum of GHG emissions, somewhere in the range of 85-161 gigatons of carbon (GtC). The upper end of this range represents one-third of all human GHG emissions since 1850.

In addition to advances in yield, today's crops have become more efficient in terms of their conversion of inputs (nitrogen, water, energy) into harvestable material (Field to Market, The Alliance for Sustainable Agriculture 2009). The advent of new traits introduced through biotechnology has further accelerated these benefits and holds the potential for step changes in both yield and input efficiency. Crops engineered to produce their own insecticide (*Bt*) are using solar energy, rather than fossil fuels, to power crop protection, which results in a measurable reduction in the carbon footprint of crop production systems. Conventional crop chemical production is associated with GHG emissions of approximately 20 kg CO₂e per kg of crop chemical produced (Wang et al. 2007). While this is a relatively modest amount of GHG emissions relative to the much larger amounts associated with tillage operations, it does represent the single most significant source of emissions for a company such as Monsanto. Monsanto has been self-reporting its emissions for more than 20 years and has been actively managing all chemical production processes in order to lower the amount released per unit of crop chemical produced.

Another widely used biotechnology trait is herbicide tolerant technology. The simplicity and agronomic advantages of herbicide tolerance crops have resulted in them now being widely grown in North America and several other world areas (Gianessi 2008). Such crops facilitate the use of conservation tillage, which provides further GHG reductions by incremental sequestration of carbon in the soil and the avoidance of fuel consumption during the tillage operation (Brookes and Barfoot 2008). In a reduced tillage system, the farmer also conserves soil, with the large decrease in CO₂ emissions sufficient to outweigh potential increases in N₂O emissions associated with higher soil moisture and less aeration (Holland 2004).

New traits in development offer the promise of further improvements in the GHG profile of crop production. These include both nitrogen use efficiency traits, which could reduce N₂O emissions; and drought tolerance traits, which could reduce the crop irrigation requirements, thereby resulting in lower use of diesel to pump ground water. Reducing the nutrient and water requirements of crops would also have clear sustainability advantages beyond only the GHG reductions, especially in areas where access to such inputs is limited (as in sub-Saharan Africa).

The Panel also found that today's advanced breeding techniques are continuously adapting the germplasm of crops to climate change by testing in a range of higher stress environments around the world. Assuming the rate of warming continues to be fairly gradual, this would suggest that advanced breeding techniques will continue to be able to keep pace. To be sure, current modeling suggests these conditions by mid-century will begin to become harmful to crop productivity, making it that much more critical to utilize all technology available to meet the world's growing food needs.

Conclusions

Unfortunately, for those of us in the scientific world, the issue of climate change has become a polarizing political issue, and is likely to remain so, given the existential threat that it represents, and the wide disparities in how it would impact the various nations of the world. For most developed countries, food security does not even register as a potential concern, and climate change is just another reason for expecting more gridlock among policymakers. However, for developing countries, agriculture and food security are daily concerns, and many are already dealing with increasing heat, moisture, and pest stress – the very same difficulties that that are predicted to worsen as climate change proceeds – hence the global dilemma.

Within this global context, Monsanto assembled the Monsanto Fellows Climate Change Panel, which found that climate change is already underway, and that rising global temperatures and changing precipitation patterns will increasingly impact agriculture. The changes will be non-uniform and are likely to increase the crop productivity advantages already enjoyed throughout much of the Americas and parts of Asia. Severe drought will become a major concern in many important regions, especially those with Mediterranean (already semi-arid) climates.

Despite these stresses and the enormity of the future challenge, the Panel found that today's agricultural production systems are secure and sufficient to meet the forecasted pace of climate change, at least through mid-century. Beyond that time, modeling suggests that crop productivity in all regions could begin to be harmed by the higher temperatures predicted for that period, unless successful GHG mitigation measures are implemented soon. By boosting yields and improving the overall sustainability profile of cropping systems, the use of modern agricultural technology has already made tremendous contributions to help reduce the overall carbon footprint of agriculture. However, there is enormous untapped potential to make further progress in this area, limited primarily by unfavourable policy toward some of those technologies, especially biotechnology. Thus, there is a pressing challenge for those engaged in production agriculture to educate all of society on how modern agricultural technology and new practices will be needed to adapt to future climate change, and even to mitigate its overall impact.

Acknowledgements

This paper would not have been possible without the support of many other scientists, including all of the climate change experts invited to assist the Monsanto Fellows Climate Change Panel, and especially the following Monsanto colleagues: David Butruille, Gregg Bogosian, Gerald Dill, Mike Edgerton, David Fischhoff, Mike Hall, Ty Vaughn, and Toni Voelker.

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Climate change in Atlantic Canada: an agricultural perspective

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Agriculture is, by definition, adaptable. However there are projected climate change impacts on the agricultural industry that will force farmers to make choices that they have never before had to consider. If the nature and extent of these impacts on agriculture could be determined, the industry may be able to develop adaptive strategies to cope with projected changes. Atlantic Canada is situated in a very diverse environmental area. The climate of the region is varied, encompassing both coastal and continental regimes and influenced by several major ocean currents and mountain ranges. Projections of climate change are available from sophisticated Global Climate Models but are only applicable over large geographical areas that encompass several climate regimes. In order to best describe the expected climate change impacts for the region, climate change scenarios and climate variables must be developed on a regional, or even site-specific scale. Application of regional scenarios for agriculture would allow the evaluation of climate change on a more site-specific scale; providing a range of temperature and precipitation values that can be used in agricultural research at a farm-scale. Recent studies into agricultural impacts in Atlantic Canada has identified the benefit of having such scenarios.

This paper reviews historical climate change in Atlantic Canada and provides scenario information recently developed by the Climate Change Section of the Meteorological Service of Canada Atlantic Operations (MSC-Atl Ops).

Additional keywords: climate change, agricultural impacts, global climate models, statistical downscaling, scenarios.

Introduction

For centuries agriculture has benefited from what has been described as a “benign” or “predictable” climate (Claque et al., 2009), especially in the Northern Hemisphere. Such predictability has led to expansion of agricultural practices, including water diversion and fertilization techniques to better provide food for an ever-increasing human population.

Successful agriculture depends on the ability of farmers to adapt to any changes that may threaten production, including climate. The more predictable the

threat, the more effective the solution the farmer chooses. Up to now, choices have been based on knowledge of past climate to develop effective increases in production.

However we now know that the climate is changing and farmers can no longer base food production choices on the past (IPCC, 2007).

Methods

The following information utilizes a geographical scale regime, where climate changes are presented at global scales first then reducing to regional scales.

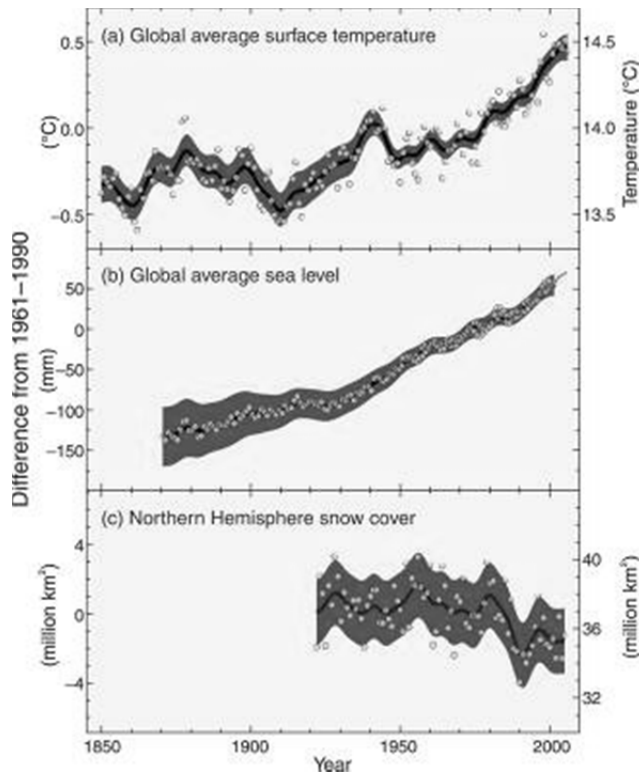


Figure 1. Observed climate changes as identified in IPCC AR4, Feb 2007 Global Temperatures.

Global Temperatures

According to the Fourth Assessment of the International Panel on Climate Change (IPCC AR4), issued in Feb 2007, “warming of the global climate is unequivocal”. Series of observations that include rising global average annual temperatures, rising global sea level, decreased snow cover and decreased arctic sea ice coverage has lead over 2000 scientists worldwide to that consensus. Not only has global average annual temperature been rising, but there are variations

geographically and seasonally in these temperature changes. Most of the warming is observed over continents rather than the oceans and at higher latitudes than at the equator. Minimum temperatures (overnight lows) have been increasing more rapidly than daytime maximums in some areas. These differences has made determining future projections of global warming more challenging, especially if we're interested at a regional scale or even at the farm scale.

Regional precipitation

Precipitation patterns are much more complex and localized. In the winter, precipitation varies from rain to snow to freezing rain, sometimes at the same location within hours. In summer, precipitation occurs as rain but varies in intensity and location.

Extreme events such as heavy rain or hail associated with convective storms in the summer or heavy snow in the winter vary in frequency across the region.

Global Model Projections

To understand how the climate system behaves, we must utilize mathematical models to describe the interactive processes that make up the heat and moisture transfer between the atmosphere, ocean and land. Such models began as one-dimensional energy transfer models in the 1980's and have since developed into multi-layered multi-dimensional realizations of the complex interactions between the atmosphere, land, oceans and cryosphere. This mathematical representation allows for calculations of climate variables at thousands of "grid-points" constructed on the globe. These values represent how the model views global climate, including mean temperature, precipitation, humidity and wind.

Around the world, over a dozen countries are running global climate models (GCMs), all attempting to best simulate global climate. In this country, the Canadian Climate Centre for Modeling and Analysis, located at the University of Victoria, BC, is responsible for developing and maintaining the current Canadian Global Climate Models (CGCM's). The latest version is CGCM4/CanCM4 (version 4) and it couples the atmosphere and ocean portions of the model to best represent the transfer of heat and moisture between them (Flato, 2000).

Once these global models have been validated against current climate, they are available to provide projections into the future. However, to best simulate the future, scenarios of how greenhouse gas emissions will behave, based on a variety of socio-economic predictions, must be added to the models. These scenarios vary from "low-emission", where action is taken to limit greenhouse gas emissions on a global scale and "high-emission" where consumption of fossil fuels continues unabated, and even grows, throughout this century.

The models are then run on large supercomputers, doing calculations for time scales out to at least 100 years in the future. Projections of climate variables are produced at the "grid-points". The scale of these "grid-points" is a box with dimensions of 300 km by 400 km. These values at the "grid-points" represent what the model thinks the climate should look like, given the particular emission scenario.

As part of the IPCC AR4, a modeling experiment utilizing global climate models from over a dozen countries, constrained by six separate emission scenarios resulted in projections of temperature change ranging from 1 to 6 Celsius by 2100 (IPCC, 2007). This means that, depending on which greenhouse gas future occurs, mean climate could warm anywhere from 1-6 C.

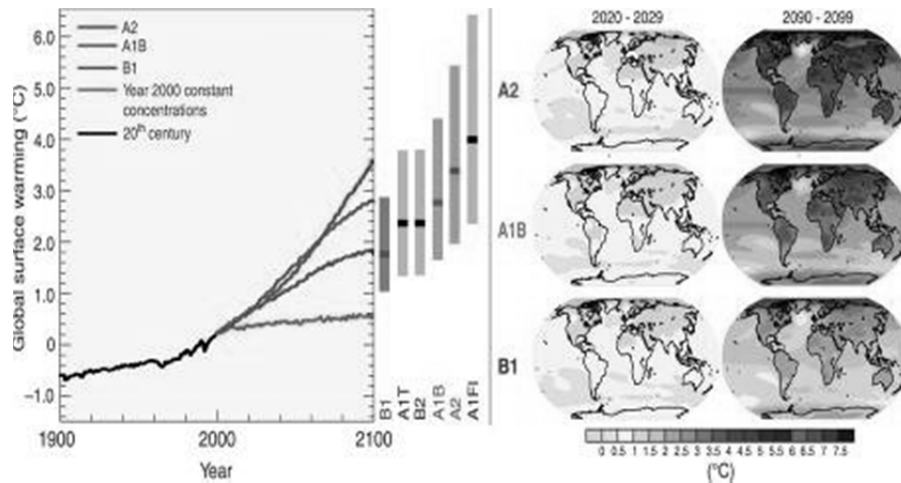


Figure 2. Projections of average temperature change based on six emission scenarios.

Anticipated global temperature and sea-level rise by 2100

The following projections were developed utilizing a suite of models and spanning the range of emission scenarios available (IPCC, 2007):

Global mean temperature is expected to increase between 1 to 6 Celsius, relative to 1990 levels by the year 2100.

Temperature increase will be uneven, and will vary regionally (eg. higher over land and polar regions, than over oceans and equatorial regions).

Thermal expansion of the oceans (water expands when heated), and the melting of polar ice-caps and glaciers will increase the mean sea-level by between 1 to 2m by the year 2100.

Warming will increase the prevalence of extremely hot days, and decrease extremely cold days. Warmer temperatures will also lead to more intense precipitation (downpours), with longer periods between rainfalls. Even if precipitation increases moderately, warmer temperatures will cause a faster rate of evaporation leading to more frequent droughts.

Results and discussion

Since the global model projections are only available on a broad (300 km x 400 km) grid, small regions that are impacted by micro-climate influences such as Atlantic Canada are not well represented by such output.

In that case, techniques to “downscale” the GCM output to achieve a scale much more appropriate for the area are utilized. An appropriate scale could be 50km x 50km or even site specific projections. The techniques vary from Regional Climate Model (RCM) output (50km grid) to statistical techniques that link local climatology to large GCMs.

The advantage of RCM output is that it represents change over the 100 year span of the projections as dynamically as possible. However due to the much larger amount of “grid-points” and calculations, it takes large amounts of computer time to produce even one scenario of climate variables. In comparison the statistical approach is much quicker and uses fewer resources, ideally running on a laptop. The disadvantage of the statistical approach is that any relationship created at current climate must hold throughout the 100 year simulation.

The Climate Change Section of MSC Atl Ops utilized a technique called the Statistical Downscaling Model (SDSM, 2002) originally developed in the UK (Wilby, 2002). While it still uses a statistical approach, it creates a relationship with a GCM and uses its ability to project for the 100 year simulation period, in order to improve on the dynamic weaknesses of the approach. The SDSM was used to create projections at 14 sites in Atlantic Canada where high quality climate data was available (Lines et al, 2005). The results provided values that represented the local climate with much more relevance than if the large scale GCM output was used alone.

In Table 1, projected temperature and precipitation changes are noted for 14 sites in Atlantic Canada on an annual basis for three tridecadal periods, the 2020’s, 2050’s and 2080’s. These values were developed by combining local climate at the sites with model parameters from the Canadian Global Climate Model, CGCM2, utilizing the SDSM technique (Lines et al, 2009).

From this information, direct impacts from a warmer, wetter climate can be quantified. As well, these values can be used to derive a series of climate indices of importance to agriculture. One such index is growing season length.

In Table 2, values of growing season length are projected into the future, again based on the CGCM2. Since the growing season index is temperature based, it is no surprise that the length of the season expands as the climate warms (Lines et al, 2009).

Table 1. Average annual projections of temperature (Tmax and Tmin) and precipitation (Pcpn) change using SDSM and CGCM2.

Annual Projected Change in Downscaled Variables with respect to 1961-1990 Baseline Period																		
	Tmax (°C)						Tmin (°C)						Pcpn (%)					
	SDSM			CGCM2			SDSM			CGCM2			SDSM			CGCM2		
	20	50	80	20	50	80	20	50	80	20	50	80	20	50	80	20	50	80
<i>Tri-decade</i>																		
<i>Nappan</i>	1.91	2.69	3.83	1.16	1.67	2.47	1.54	2.15	3.08	1.77	2.40	3.36	-1	3	4	0	6	3
<i>Kentville</i>	1.99	2.85	3.98	1.16	1.67	2.47	1.46	2.06	2.97	1.77	2.40	3.36	4	7	8	0	6	3
<i>Greenwood</i>	1.76	2.58	3.68	1.16	1.67	2.47	1.54	2.13	3.04	1.77	2.40	3.36	15	17	19	0	6	3
<i>Shearwater</i>	1.52	2.15	3.11	1.16	1.67	2.47	1.54	2.09	2.88	1.77	2.40	3.36	8	12	12	0	6	3
<i>Sydney</i>	1.18	1.92	3.37	1.06	1.42	2.12	1.76	2.52	3.69	1.12	1.49	2.21	14	16	19	3	3	4
<i>Fredericton</i>	1.68	2.30	3.31	1.19	1.65	2.32	1.72	2.25	3.06	1.84	2.46	3.50	8	13	18	-2	5	5
<i>Moncton</i>	1.99	2.80	3.91	1.16	1.67	2.47	1.72	2.36	3.30	1.77	2.40	3.36	2	3	6	-1	5	4
<i>Saint John</i>	1.46	1.99	2.82	1.19	1.65	2.32	1.61	2.06	2.77	1.84	2.46	3.50	10	13	16	-2	5	5
<i>Charlottetown</i>	1.70	2.46	3.51	1.16	1.67	2.47	1.69	2.33	3.34	1.77	2.40	3.36	13	16	18	0	5	4
<i>Gander</i>	1.97	2.77	3.94	1.31	1.85	2.67	1.49	2.14	3.09	1.97	2.82	3.96	3	4	7	2	3	3
<i>St Johns</i>	0.43	1.36	3.02	0.44	0.86	1.64	1.16	2.0	3.45	0.49	0.92	1.72	18	22	26	2	-3	1
<i>Cartwright</i>	2.25	2.92	4.34	0.84	1.29	2.05	2.04	2.90	4.16	1.77	2.62	3.79	-12	-8	-5	1	4	2
<i>Goose Bay</i>	2.25	2.95	4.01	1.96	2.73	3.87	1.95	2.78	3.87	2.31	3.34	4.83	3	6	10	1	3	5
<i>Stephenville</i>	0.67	1.67	2.83	1.14	1.84	2.75	1.84	2.58	3.63	1.93	2.67	3.62	12	16	20	-1	5	1

Table 2. Changes in growing season length based on downscaling of CGCM2

Growing Season Length (days)				
Period	Hist	2020s	2050s	2080s
<i>Nappan</i>	170	181	191	196
<i>CGCM2</i>				
<i>Kentville</i>	186	196	207	213
<i>CGCM2</i>				
<i>Shearwater</i>	184	194	200	207
<i>CGCM2</i>				
<i>Greenwood</i>	181	191	200	212
<i>CGCM2</i>				
<i>Fredericton</i>	172	178	186	191
<i>CGCM2</i>				
<i>Moncton</i>	173	184	192	200
<i>CGCM2</i>				
<i>Saint John</i>	182	185	189	198
<i>CGCM2</i>				
<i>Charlottetown</i>	184	184	191	201
<i>CGCM2</i>				
<i>Charlottetown</i>	184	200	208	221
<i>HadCM3</i>				
<i>Gander</i>	170	182	192	197
<i>CGCM2</i>				
<i>St Johns</i>	182	188	194	219
<i>CGCM2</i>				
<i>Cartwright</i>	135	169	168	181
<i>CGCM2</i>				
<i>Goose Bay</i>	138	151	157	161
<i>CGCM2</i>				

Conclusions

The impacts on agriculture of a warming climate can be direct, such as heat waves from extreme maximum temperatures or indirect, such as applying climate indices (growing season length) to calculate potential changes to food production.

As well, models are projecting a change in character of precipitation globally, not just an increasing annual amount. As the century moves forward, the precipitation pattern will shift to more heavy events over fewer days, leaving longer periods of dryness. Such changes can create new variability in how precipitation behaves, on both an annual and seasonal basis, and make decision based on past climate behaviour difficult and possibly erroneous.

Such changes may force agricultural producers to determine how to adapt their practices to best suit a warmer climate. That adaptation will be based on these expected impacts (Lemmen, 2008):

Changes in mean climate will affect decisions concerning long-term crop selection. One example is fruit-tree growth. Most species require 15-20 years to mature then produce for 10-15 years after that. Average climate changes on a 20-30 years' time frame may impact that growth and production cycle.

Increases in extreme temperature and precipitation events will threaten the successful production and harvest period for most crops. Extended drought, diminishing snow cover and severe weather (e.g. hailstorms) will be a main area of concern.

In order to best adapt, two approaches must be considered by producers.

First, a re-examination of cropping systems and techniques must be undertaken. This includes determining appropriate crop selection based on long-term projected changes, actively performing sustainable soil management practices and determining the most effective pest and weed control.

Secondly, an emphasis must be placed on increased water management. With increase heavy precipitation, consideration must be given to improved drainage and erosion control. On the other hand, with extended dryness, on-farm or regional water management/storage for irrigation must be examined.

Acknowledgements

I thank my Director, Mr. Bill Appleby, of the Meteorological Service of Canada Atlantic Operations for the financial support that allowed me to attend this conference.

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Range expansion of kochia (*Kochia scoparia*) in North America under a changing climate

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Climate is the principal determinant of vegetation distribution and abundance. *Kochia scoparia* (L.) Schrad. (kochia) expansion northward in the Canadian Prairies is partially attributed to climate change. We developed and validated a bioclimatic model for the species using CLIMEX software to estimate how climate change will affect potential range of kochia across North America. Model parameters were derived from the literature or experimental data, and adjusted for best fit of simulated (current climate-modeled values of the ecoclimatic index (EI) that quantifies the climatic suitability of a location to support a self-sustaining population) to actual kochia distribution and abundance in its native range in Europe and Asia. The EI values correlated well with relative abundance of kochia in Canadian provinces and American states. With unchanged precipitation, temperature increases of 1 to 3 C results in range expansion of kochia in the United States mainly eastward into the Midwest and Atlantic regions; in Canada, its range expands primarily into the interior of British Columbia, northern Prairies, and northern Ontario. The length of the growing season or accumulated heat units limits its northern range expansion. Twenty percent greater precipitation than current climate normals mitigates population expansion in eastern North America, whereas 20% less precipitation exacerbates the effect of increasing temperatures. Thus, a changing climate has the potential to markedly expand the current range of kochia.

Additional keywords: bioclimatic model, climate change, CLIMEX, herbicide resistance, invasive weeds

Introduction

Climate is the main factor determining vegetation distribution and abundance (Sutherst 2000; Woodward and Williams 1987). Global annual mean temperature is predicted to rise by 1.5 to 4 C by 2100, as a consequence of increased atmospheric levels of greenhouse gases such as CO₂ (Patterson 1995; Quarles 2007). Although elevated levels of CO₂ generally increase the growth or competitive ability of C₃ plants more than that of C₄ plants, a concomitant warmer climate will likely offset this advantage or even result in the opposite effect (Fuhrer

2003; Patterson et al. 1999). Past studies strongly suggest that geographic range transformations of agricultural weeds are highly probable outcomes from global climate change (Fuhrer 2003; Patterson 1995). The range expansion of many weeds into higher latitudes of the northern hemisphere may accelerate with global warming. For individual weeds, poleward range expansion resulting in adverse effects on crop yield may range from 200 to 600 km by the end of the century (McDonald et al. 2009). The northern limit of warm-temperate annual species is primarily set by the heat units (degree-days) accumulated during the growing season (Patterson et al. 1999). Leeson and Beckie (2012, this volume) similarly found that growing degree-days or growing season length was the main climatic factor determining weed species distribution across western Canada.

Bioclimatic models (also referred to as bioclimate envelope, ecological niche, or species distribution models) have been used to predict potential distribution and relative abundance of insects, plants, and pathogens (Jeschke and Strayer 2008). The standard species-distribution (or niche) models, such as BIOCLIM (Muñoz et al. 2010), MaxEnt (Phillips et al. 2006), GARP (Stockwell and Peters 1999), and BioSim (Régnière et al. 1995), use known species presence or absence data together with climate data to fit a relationship between climate and occurrence as a basis for prediction. Unlike other models that are of a general statistical nature and can be used for any type of problem, the CLIMEX (climate-matching and inferential-modeling) model (Sutherst and Maywald 1985) is designed to be used with organisms and requires species-specific biological and ecological data. It has frequently been used to simulate potential distribution and abundance of crop pests, such as *Abutilon theophrasti* Medicus (velvetleaf) or *Oulema melanopus* (L.) (cereal leaf beetle) (e.g., Holt and Boose 2000; Olfert and Weiss 2006). Our familiarity and experience with the model were facilitated by close collaboration between entomologists at Agriculture and Agri-Food Canada and CSIRO (Commonwealth Scientific and Industrial Research Organisation), who originally developed the software.

All simulation models are limited to varying degrees in the accuracy of their predictions because of model mis-specification or faulty assumptions. Bioclimatic models are based on the assumptions that species are limited by climate, which can be estimated by long-term averages, and that the species currently occupies the full range of suitable climates within its native habitat (Cruttwell McFadyen 1991). Predicted potential distribution as delimited by the bioclimatic niche may not be equivalent to the actual distribution because of (1) biotic interactions that may not remain constant over time, i.e., species' ranges may diverge or converge and therefore lead to new communities or interactions; (2) genetic, phenotypic, or ecotypic composition of populations that may change spatially and temporally; (3) some restrictions on the dispersal of most species because of their biology and ecology or degree of connectivity of landscapes suitable for dispersion; (4) edaphic factors such as soil profile development, degree of disturbance, texture, fertility, etc.; or (5) type of plant communities or ecosystems (e.g., mature forest; wetlands, etc.) (McDonald et al. 2009; Pearson and Dawson 2006).

Kochia scoparia (L.) Schrad. (kochia) is an annual C₄ tumbleweed that is native to Eurasia (reviewed by Friesen et al. 2009). The species occurs in small-grain crop production systems and ruderal (non-crop disturbed) areas in semiarid to arid regions of North America. Among weeds, kochia has increased in relative abundance across the Canadian Prairies at the second-highest rate over the past 40 yr; it is now the 10th most abundant weed of arable fields (Leeson et al. 2005). In addition, the range of kochia is expanding northward in the Prairies, as indicated by weed surveys conducted from the 1970s to 2000s (Thomas and Leeson 2007).

The range expansion of kochia may be related to a longer growing season. During the past 40 yr, the frost-free growing season on the Prairies has increased by up to 4 d, varying somewhat from region to region (Gitay et al. 2002). From 2007 to 2009, kochia was observed for the first time at multiple sites in northern Manitoba, northern Saskatchewan (Saskatoon north to Prince Albert) and the Peace River region of Alberta (H. Beckie, unpublished data).

Most kochia populations in western Canada are now acetolactate synthase (ALS) inhibitor-resistant (Beckie et al. 2011; Warwick et al. 2008). A pleiotropic effect of the *ALS* mutation is seed germination at cooler soil temperatures than susceptible biotypes (Dyer et al. 1993; Thompson et al. 1994). Moreover, ALS-inhibitor herbicide use is greatest in the northern Prairies (Leeson et al. 2004), thereby conferring a fitness or selective advantage for resistant vs. susceptible biotypes. In the United States, ALS-inhibitor resistance in kochia also is widespread; additionally, a number of kochia populations from Kansas have been confirmed as glyphosate-resistant (Heap 2011).

Thus, a longer frost-free growing season combined with widespread herbicide resistance likely favoured the observed northern range expansion of kochia. We hypothesize that a future warmer climate with variable precipitation will further alter the geographic distribution of the species. In this study, we utilize the CLIMEX model to delineate the future potential suitability of geographic regions across North America for kochia populations under various climate-change scenarios. Olfert et al. (2012, this volume) extend this modeling approach by applying general circulation model scenarios to the bioclimatic model of kochia.

Materials and methods

CLIMEX model description

CLIMEX model version 3.0 computes temperature, moisture, and light indices for a species by calculating the number of days these meteorological data from a site fall within user-specified parameters (Sutherst and Maywald 1985; Sutherst et al. 2007). These indices comprise limiting low, lower optimum, upper optimum, and limiting high values. The indices are integrated into a growth index (GI). The GI is then combined with stress-related indices: cold and heat, dry and wet, and their interactions. The resultant ecoclimatic index (EI) quantifies the climatic suitability of a location for the species of interest. Greater EI values indicate greater potential of a given location to support a self-sustaining population.

Model development and validation

Model parameters for kochia were derived from the literature (Friesen et al. 2009), and supplemented with experimental weed biology data (Leeson et al., unpublished data). Model parameters and their values are listed in Table 1. On the basis that climate is the main factor determining plant distribution and abundance, parameter values were adjusted where necessary for best fit of simulated (EI values) to actual distribution and abundance of the species in its native range in Europe and Asia.

Distribution and abundance of kochia in Europe and Asia were derived from published reports, databases, and floras (e.g., Czerepanov 1995; Holmgren et al. 1990; Hultén 1971; Jalas and Suominen 1980; Mosyakin 2003; Murin and Svobodová 1992; Shu 2003). The minimum degree-days for kochia development (per generation) was set at 825 (Table 1) (Friesen et al. 2009). The goodness of fit between simulated (EI values) to actual distribution and abundance of kochia in its introduced range in North America was evaluated. Although EI quantifies the climatic suitability of a location, it may be positively related to species abundance as climate is the principal determinant of vegetation distribution (e.g., Sutherst 2000; Woodward and Williams 1987). Relative abundance ranking (scale of 0 to 3 where 0 = absent, 1 = relatively low abundance, 2 = relatively moderate abundance, 3 = relatively high abundance) of kochia in Canadian provinces, American states, and various regions of Mexico (e.g., Leeson et al. 2005; USDA-NRCS 2008) were linearly correlated with EI values in the respective jurisdictions ($n=50$). The significance of the correlation coefficient, r , was determined at $P=0.05$ (Little and Hills 1978).

The global climate dataset (years 1961-1990; New et al. 1999) was provided with CLIMEX. The dataset comprises surface climatology values for nine variables per grid cell, each measuring 0.5° latitude (ca. 56 km) by 0.5° longitude (at equator: ca. 56 km; at 60° N latitude: ca. 28 km). The number of grid cells for climate data for Europe and Asia was 6,416 and 22,191, respectively. Climate data for North America comprised 12,452 grid cells.

Model simulations

Climate-change scenarios were generated using an incremental approach. A factorial combination of temperature (three levels) and precipitation (three levels) was investigated. Temperatures were +1, +2, and +3 C of climate-normal temperature for each grid, with precipitation unchanged (0%), +20%, or -20% of climate-normal precipitation for each grid (years 1961-1990). Contour maps of EI values were constructed using ArcView software.¹

Table 1. Parameters and values used in the CLIMEX model for kochia.

Category	Parameter	Abbreviation	Value
Temperature (C)	Lower temperature threshold	DV0	9
	Lower optimum temperature	DV1	18
	Upper optimum temperature	DV2	32
	Upper temperature threshold.	DV3	40
Growing degree- days (d)	Minimum required for development ^a	PDD	825
	Moisture ^b (% soil capacity)		
	Limiting low soil moisture threshold	SM0	0.08
	Lower optimum soil moisture	SM1	0.12
	Upper optimum soil moisture	SM2	0.35
	Limiting high soil moisture.	SM3	1.30
Light (h)	Daylength above which growth is maximum	LT0	16.0
	Daylength below which growth is zero	LT1	11.8
Stress indices	Cold stress threshold (avg. weekly minimum temperature, C)	TTCS	-12
	Heat stress threshold (avg. weekly maximum temperature, C)	TTHS	40
	Dry stress threshold (avg. weekly minimum soil moisture, % soil capacity)	SMDS	0.02
	Wet stress threshold (avg. weekly maximum soil moisture, % soil capacity)	SMWS	2
	Cold stress accumulation rate (weekly cold stress / avg. weekly minimum temperature)	THCS	-0.0004
	Heat stress accumulation rate (weekly heat stress / avg. weekly maximum temperature)	TTHS	0.008
	Dry stress accumulation rate (weekly dry stress / avg. weekly minimum soil moisture)	HDS	-0.003
	Wet stress accumulation rate (weekly wet stress / avg. weekly maximum soil moisture)	SHWS	0.001

^a Minimum growing degree-days required for development per generation (base 0 C).

^b SM0, SM1, SM2, SM3: all are expressed as a percentage of the maximum soil storage capacity of 100 mm (Rogers et al. 2007; Sutherst and Maywald 1985).

Results and discussion

Model development and validation were successfully completed after EI values of kochia in its native range in Europe (Figure 1) and Asia (Figure 2), and in its introduced range in North America (Figure 3) were found in closest agreement with actual kochia distribution and abundance. In this study, EI values for a location ≤ 5 indicate relatively poor suitability, whereas values > 15 indicate relatively good suitability for sustained populations that result in potential economic crop yield loss. Relative abundance ranking of the species in Canadian provinces, American states, and regions of Mexico ($n=50$) generally corresponded well with EI values in the respective jurisdictions. The correlation coefficient, r , was 0.86, significant at $P < 0.05$ (Little and Hills 1978). For some of the 50 sites examined, EI values did not correspond well with abundance ranking. For example, EI values of ≤ 15 were indicated in Florida or Arkansas (Figure 3); however, kochia is not known to occur in these states (N. Polge, N. Burgos, personal communication). In these cases where discrepancies were noted, the habitat (e.g., soil type or degree of disturbance, type of plant community, etc.) may be unsuitable for kochia establishment or dispersal.

As documented in various floras, kochia is associated with continental climates and is most abundant in regions with warm, dry growing seasons. In agreement with the results of multivariate statistical analysis of the impact of climate on Canadian Prairie weed distributions (Leeson and Beckie 2012, this volume), model sensitivity analysis in this study indicated that the main factor limiting the northern range expansion of the species in Canada is the length of the growing season (or accumulated growing degree-days) required to complete one generation.

Model simulations indicated that the response of EI to increasing temperature (precipitation unchanged) varied markedly by location. For example, EI values at Dallas, Texas are predicted to decline in response to increasing temperature (Figure 4), because the upper temperature and/or lower moisture threshold is exceeded. At Harrow (southwestern Ontario) or Lethbridge (southern Alberta), EI values are relatively insensitive to temperature change. In contrast, EI values increase markedly in response to a temperature increase of 1 C above current climate at Peace River, Alberta, because the growing season in most summers currently is too short to permit completion of one kochia generation (authors, personal observation).

With unchanged precipitation, incremental temperature increases of 1 to 3 C results in range expansion of kochia in Canada into the interior of British Columbia, the northern Prairies including the Peace River region of Alberta, northern Ontario, and to a lesser extent, parts of southern Québec and the Maritimes (Figures 5 to 7). However, lack of suitable habitat in parts of these previously-unoccupied areas, such as mature forest, wetlands, exposed bedrock, etc., would be a deterrent to colonization or establishment. For example, the Boreal Shield ecozone, spanning the Prairies to the Maritimes, is generally characterized by forests and exposed bedrock with poor soil development (Natural Resources Canada 2010).

With unchanged precipitation in the United States, kochia is shown to expand primarily eastward into the Midwest and Atlantic regions as temperature increases by 1 to 3 C. In contrast to Canada and the Midwest and Atlantic regions of the United States, a warming climate with unchanged precipitation is expected to restrict the distribution and abundance of kochia in other regions of the United States and throughout Mexico. In these regions, upper temperature or lower moisture thresholds, or both, for sustained kochia populations are likely to be exceeded.

Enhanced precipitation is predicted to modify the influence of warmer temperatures on the range expansion of the species. Twenty percent greater precipitation than current climate normals mitigates population expansion of this drought-tolerant weed into eastern North America (Figures 5 to 7). Therefore, in these eastern regions where 20% greater precipitation than current-normal precipitation accompanies increased temperatures, the upper moisture threshold of the weed will likely be exceeded. An increase in precipitation of this magnitude is predicted to offset the potential range expansion of kochia resulting from even a 3 C rise in climate-normal temperature (Figure 3 vs. Figure 7). In contrast, 20% less precipitation exacerbates the effect of increasing temperatures because the species is best adapted to warm, dry climates (Figures 5 to 7). In general, model simulations of kochia's range seem to be most sensitive to changes in moisture-related parameter values. With climate change, precipitation patterns across North America are expected to be more stochastic and less predictable than that of temperature (Gitay et al. 2002). Thus, potential range expansion of kochia into different regions of North America under a warming climate will be closely linked to how precipitation distribution and abundance are altered from current patterns.

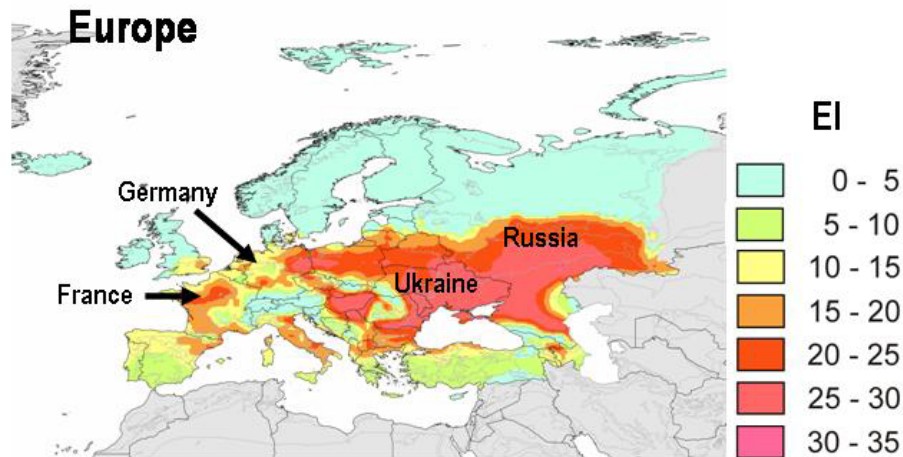


Figure 1. Kochia distribution and relative abundance (current climate) as depicted by contours of ecoclimatic index (EI) values for the species in Europe.

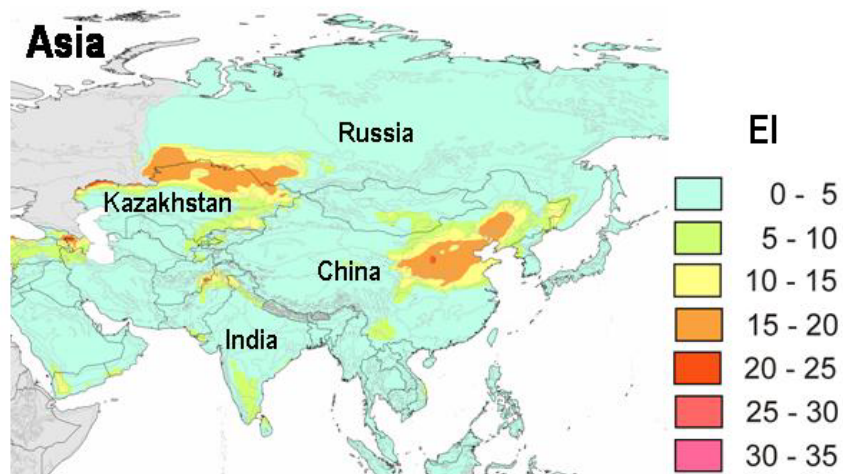


Figure 2. Kochia distribution and relative abundance (current climate) as depicted by contours of eoclimatic index (EI) values for the species in Asia.

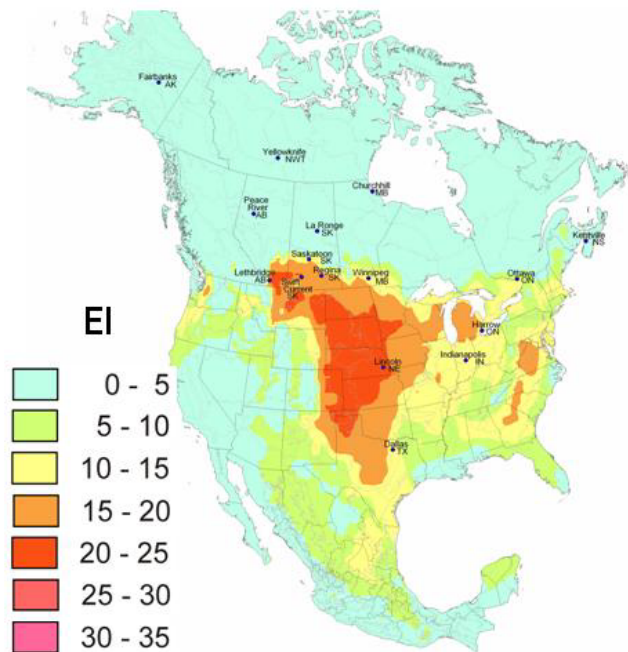


Figure 3. Kochia distribution and relative abundance (current climate) as depicted by contours of eoclimatic index (EI) values for the species in North America.

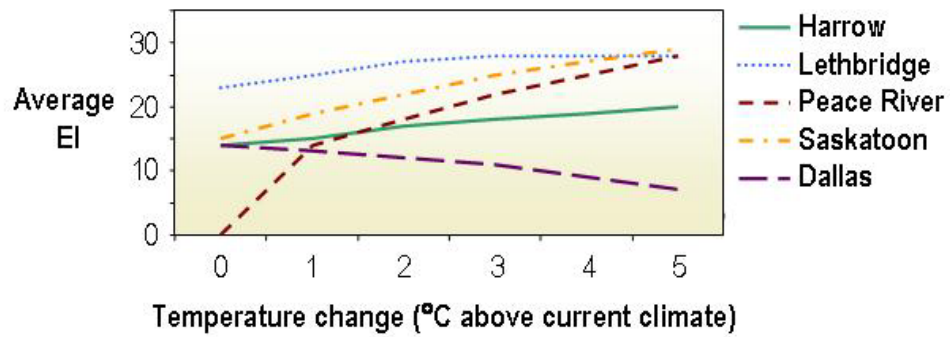


Figure 4. Response of ecoclimatic index (EI) to increasing temperature at five selected locations throughout North America: Harrow, Ontario; Lethbridge, Alberta; Peace River, Alberta; Saskatoon, Saskatchewan; and Dallas, Texas.

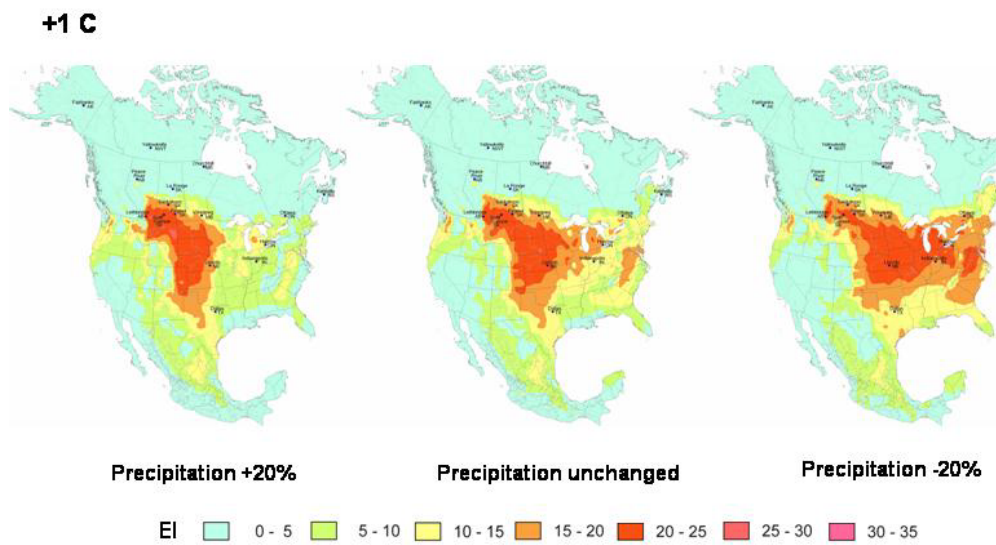


Figure 5. Kochia distribution and relative abundance: climate-change scenario of +1 C of climate-normal temperature for each grid, with unchanged or +/- 20% of climate-normal precipitation for each grid.

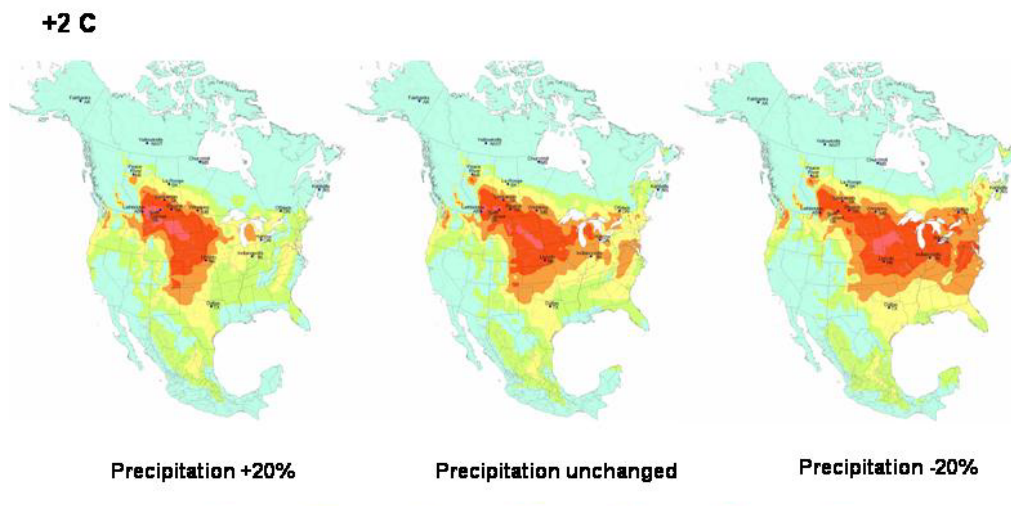


Figure 6. Kochia distribution and relative abundance: climate-change scenario of +2 C of climate-normal temperature for each grid, with unchanged or +/- 20% of climate-normal precipitation for each grid.

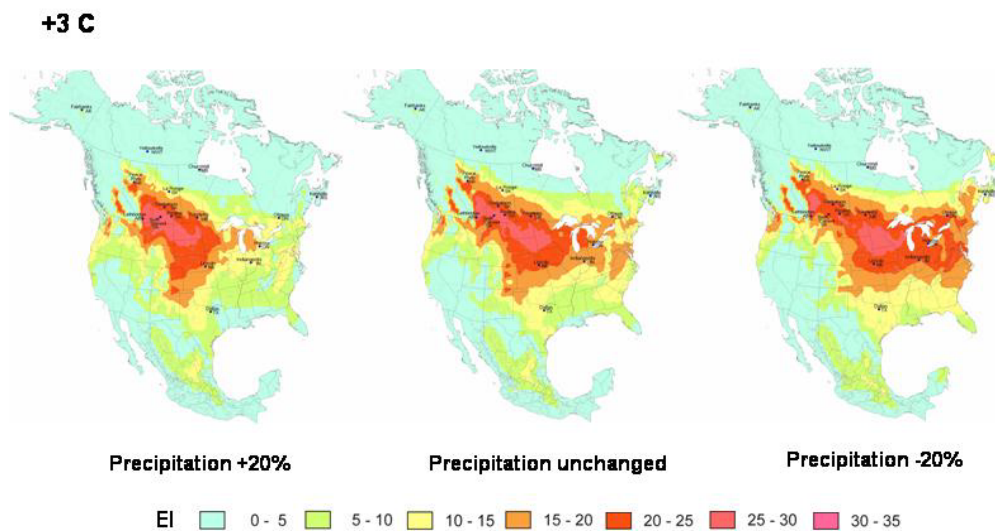


Figure 7. Kochia distribution and relative abundance: climate-change scenario of +3 C of climate-normal temperature for each grid, with unchanged or +/- 20% of climate-normal precipitation for each grid.

Overall, the results of this study are similar to the general circulation model scenarios of the kochia bioclimatic model (Olfert et al. 2012, this volume). In the latter study, the range and relative abundance of kochia expanded across North America – particularly north and west to include most of the Canadian Prairies – and contracted in the southern United States and Mexico.

Notwithstanding their inherent limitations, bioclimatic models can be a useful tool in identifying weed species, such as kochia, whose current range may be most affected by a warming climate with variable precipitation. In contrast to kochia, the distributions of some weed species in the Canadian Prairies are expected to be relatively climate-change insensitive. For example, in this region, 24 of the 60 most common weed species had less than 20% of the variance in their distribution associated with climate (Leeson and Beckie 2012, this volume). In addition, geographic regions that are likely to be at greatest risk of invasion from climate change-sensitive species, such as kochia in this study, can be identified. By providing advanced notification of the potential invasiveness of specific weeds as a result of a changing climate, those involved in weed research or extension will have a wide window of opportunity to develop and transfer integrated best management tactics and practices to mitigate population expansion of these species. Through increased awareness, growers or land managers in potentially high-risk areas can be more proactive in monitoring or detection, and will have useful information, when needed, on recommended practices to combat the establishment or spread of these weed species.

Sources of materials

¹ArcView software 8.1, ESRI Incorporated, 380 New York Street, Redlands, CA 92373-8100, USA.

Acknowledgments

We thank David Giffen, AAFC Saskatoon, for producing the maps, and Dr. Ardath Francis, AAFC Ottawa, for assistance in compiling kochia global distribution and abundance data.

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Bio-climatic approach to assessing the potential impact of climate change on representative crop pests in North America

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The dominant factor determining the distribution and abundance of most insects, plant pathogens and plant vegetation is climate. The impact of climatic changes caused by human activities and the effects on agriculture has raised concern in recent years. The potential implications for integrated crop management are numerous. Bioclimate simulation models were used to predict the distribution and extent of crop pest establishment in new environments. General circulation model scenarios were applied to bio-climatic models of the weed *Kochia scoparia* (kochia), the pathogen *Fusarium graminearum* (fusarium head blight), and the insect *Oulema melanopus* (cereal leaf beetle) to assess the potential impact of climate change on species distribution and relative abundance. Results for the three general circulation model scenarios indicated that all three crop pests would have increased range and relative abundance in more northern regions of North America,

compared to predicted range and distribution under current climatic conditions. Conversely, model output predicted that climate conditions would become limiting for these species in some southern regions of North America and could cause a decrease in the distribution range, seasonal development or relative abundance.

Keywords: *Kochia scoparia*, *Fusarium graminearum*, *Oulema melanopus*, bioclimate model, climate change

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Introduction

The dominant factor determining the distribution and abundance of most insects, plant pathogens and plant vegetation is climate (Sutherst 2000a; Woodward and Williams 1987). Rosenzweig et al. (2000) reported that the overall global temperature has increased 0.7 °C over the last 100 years, and that the 1990's has been the warmest decade on record. Climate change scenarios have predicted that temperatures will increase by 1 - 3 °C for low greenhouse gas emissions and 3.5 - 7.5 °C for high gas emissions over the next 100 years (Cohen and Miller 2001). However, Walther et al. (2002) suggest that species respond more directly to regional changes that are highly heterogeneous than to approximated global averages. Many species have already responded to regional conditions that have occurred during the 20th century. In a study of 694 animal and plant species, Root et al. (2003) investigated the change in timing of events over the past 50 years and reported that timing of phenological events (i.e. breeding, blooming) occurred 5.1 days earlier per decade. The potential effects of a warmer climate on agricultural pest species include extending the growing season, altering the timing of germination for weeds, seasonal development of plant diseases or emergence from overwintering sites for insects, increasing growth and development rates, shortening generation times, increasing their reproductive capacities and changing their geographic distributions (Porter et al. 1991; Gitay et al. 2001).

Current climate analogues have been used to identify geographic regions that may be susceptible to establishment of agricultural pest species and have been used to compare the results of climate change scenarios to those regions where they are already established (Sutherst et al. 1996). The magnitude of predicted temperature change associated with climate change is not within the historical experience of modern agriculture. As a result, historical data cannot be used with confidence as analogues to predict the impact of climate change on crop pests. However, bioclimate simulation models, based on general circulation model (GCM)

inputs, have been used to assess impact and related system vulnerability for future climates.

Bioclimate simulation models have been applied successfully to predict the distribution and extent of insect establishment in new environments (McKenney et al. 2003; Sutherst and Maywald 2005; Mika et al. 2008; Olfert et al. 2011). Bioclimatic modeling software, such as CLIMEX[®], facilitates the development of models that describe the potential distribution and relative abundance of a species based on climate (Sutherst 2000b). CLIMEX[®] derives an Ecoclimatic Index (EI) which describes the suitability of specific locations for species survival and reproduction. Model parameters include temperature (TI), diapause (DI), light (LI), moisture (MI), heat stress (HS), cold stress (CS), wet stress (WS) and dry stress (DS). The EI values are obtained by combining a Growth Index (GI) with stress indices (dry, wet, cold, and hot) that describe conditions that are unfavourable for growth.

Bioclimate models were developed to predict the potential distributions and relative abundances of three crop pests: kochia [*Kochia scoparia* (L.) Schrad.], *Fusarium graminearum* Schwabe and cereal leaf beetle [*Oulema melanopus* (L.)] within North America (Beckie et al. 2012, this volume; Turkington et al. 2011; Olfert et al. 2004). Kochia is a C4 tumbleweed, native to Eurasia, which occurs in crop production systems and rural areas in semiarid to arid regions of North America (Friesen et al. 2009). The range of kochia is expanding northward in the Northern Great Plains, as indicated by weed surveys conducted from the 1970s to early 2000s (Thomas and Leeson 2007). Most kochia populations in western Canada are now acetolactate synthase (ALS) inhibitor resistant (Beckie et al. 2011). Bioclimate model results for kochia, based on incremental temperature (+1 °C to +7 °C) and precipitation (-60% to +60%), indicated that the potential population distribution would undergo marked changes from its current range (Beckie et al. 2012, this volume). In that study, sensitivity analysis indicated that northward expansion was limited by growing season length and that warmer conditions associated with climate change could result in northward range extension, including potential encroachment into the Peace River region of Alberta.

Fusarium graminearum is the main causal agent of fusarium head blight (FHB) and is an important cereal disease across eastern Canada, Manitoba and the mid-western United States (Clear and Patrick 2010; Gilbert and Tekauz 2000; McMullen et al. 1997b; Menzies and Gilbert 2003; Tekauz et al. 2000). Infection of cereal heads by this pathogen can result in not only significant yield losses but the resulting fusarium damaged kernels in wheat (*Triticum* spp. L) can also reduce market grades (Wiese 1987; Menzies and Gilbert 2003). The fungus can produce several mycotoxins, including deoxynivalenol (DON) and zearalenone. In non-ruminants, DON-contaminated feed can reduce growth rates while zearalenone can cause reproductive problems (Charmley et al. 1996; D'Mello et al. 1999; D'Mello and Macdonald 1997). Barley (*Hordeum vulgare* L.) infected with *F. graminearum*

and contaminated with DON can also cause quality problems for the malting and brewing industries (Schwarz 2003). A bioclimate modeling project, based on incremental scenarios for combinations of temperature (-3°C to $+3^{\circ}\text{C}$) and precipitation (-30% to $+30\%$) conducted by Turkington et al. (2011) predicted that, for current climates, *F. graminearum* could expand from its current range primarily in eastern prairies across large areas in Saskatchewan and Alberta, in particular, the Edmonton and surrounding region of Alberta, and south towards Calgary and east towards Lloydminster. This is an area with approximately 25-40% of the wheat and barley acreage in Alberta (Alberta Agriculture and Rural Development 2010). Further, the model demonstrated that *F. graminearum* was more sensitive to rainfall than temperature, while an irrigation scenario indicated that *F. graminearum* could have significant implications for irrigated fields in the central to western prairies.

The cereal leaf beetle is an invasive insect pest of small grain crops, particularly wheat, oats (*Avena sativa* L.) and barley (CAB International 2002). The species was first reported in Michigan in 1962 and is now present across much of North America (Olfert et al. 2004; Dossall et al. 2008). A bioclimate model, developed to predict potential range and relative abundance of cereal leaf beetle in North America, was used to predict the impact of incremental changes in climate in Canada (Olfert et al. 2004; Olfert and Weiss 2006). The study was based on incremental scenarios for combinations of temperature ($+1^{\circ}\text{C}$ to $+7^{\circ}\text{C}$) and precipitation (-60% to $+60\%$). Compared to current climate, results indicated that cereal leaf beetle range and abundance would increase and extend to regions where it would not currently exist in Canada.

Mika et al. (2008) reported that climatic variables can vary both spatially and temporally at an ecosystem level. As such, incremental scenarios based on temperature and precipitation changes for grid cells as applied in the three studies mentioned, only exhibit spatial variation. Therefore, they suggested that the widely accepted and more commonly used GCMs should be used in conjunction with bioclimate models, rather than base climate change analysis on incremental temperature and precipitation changes. Further, they encouraged the application of multiple GCMs due to the variability of climate projections between models.

The objective of this study was to use the bioclimate models for *K. scoparia*, *F. graminearum* and *O. melanopus* to assess the impact of three general circulation models on population distribution and relative abundance of three crop pest species across North America.

Methods

Bioclimatic models were developed using CLIMEX[®] 2.0 (*O. melanopus*) and CLIMEX[®] 3.0 (*K. scoparia*, *F. graminearum*) (Sutherst et al. 2004, 2007). CLIMEX[®] is a dynamic model that integrates the weekly responses of a population

to climate using a series of annual indices. It uses an annual Growth Index (GI) to describe the potential for population growth as a function of soil moisture and temperature during favourable conditions, and Stress Indices (cold, wet, hot, dry) to determine the effect of abiotic stress on survival in unfavourable conditions. The weekly Growth Index is a function of temperature (TI), diapause (DI), and moisture (MI). The growth and stress indices are calculated weekly and then combined into an overall annual index of climatic suitability, the Ecoclimatic Index (EI), that ranges from 0 for locations where the species are not able to persist to 100 for locations that are optimal for the species. Depending on model requirements, resulting EI values and subsequent interpretation of EI values, may vary between species. For example Beckie et al. (2012, this volume) determined that $EI < 5$ would indicate regions that have unsuitable climate for establishment of kochia and EI values > 15 would suggest regions that could support plant densities that could result in economic loss if not managed. As a result, EI values for kochia were categorized as 'unfavourable' ($EI \leq 5$), 'suitable' ($EI = 5 < 15$), 'favourable' ($EI = 15 < 20$) and 'very favourable' ($EI = > 20$). For cereal leaf beetle, EI values were categorized as 'unfavourable' ($EI < 10$), 'suitable' ($EI = 10 < 20$), 'favourable' ($EI = 20 < 30$) and 'very favourable' ($EI = > 30$). Given that *F. graminearum* has a worldwide occurrence (CAB International 2003), moisture or temperature stress imposed during the overwintering period was considered negligible and thus no stress parameters were included in the model. As a result, EI values are equivalent to GI values under these conditions. Annual EI (GI) values of less than 10 indicate areas where FHB caused by *F. graminearum* either typically does not appear, or if it does, its growing season development is very limited and it would only be expected to occur at trace levels. The 'suitable' category ($EI = 10 < 20$) describes climatic conditions where limited FHB outbreaks are expected to occur, while EI values of $20 < 30$ and > 30 would be categorized as 'favourable' and 'very favourable', respectively, for seasonal FHB development. Model parameter values for the three species are listed in Table 1.

Three general circulation models were selected to cover a range of climate sensitivities, based on A1B emission scenario (CRU - Climate Research Unit, East Anglia, UK). They were obtained as monthly means from the Intergovernmental Panel on Climate Change (IPCC 2007). The range of climate sensitivities is defined as the amount of global warming for a doubling of the atmospheric CO_2 concentration compared with 1990 levels (Kriticos et al. 2006). The three GCMs selected were CSIRO Mark 3.0 (CSIRO, Australia), NCAR273 CCSM (National Centre for Atmospheric Research, USA), and MIROC-H (Centre for Climate Research, Japan). The respective sensitivities are CSIRO Mark 3.0 (2.11 °C), NCAR273 CCSM (2.47 °C), and MIROC-H (4.13 °C). All three also had relatively small horizontal grid spacing and the requisite climatic variables at a temporal resolution appropriate for CLIMEX[®]. The data were pattern-scaled to develop individual change scenarios relative to the base climatology (Whetton et al. 2005).

The resulting database was queried to analyze data at a regional scale. A geographic rectangle, 4° latitude by 7° longitude, was used to delineate a regional template (approximately 270,000 km²) consisting of 112 grid cells for each dataset. Specific regions, based on latitude and longitude coordinates, were defined and output (averaged across the region) was generated for detailed analysis. The datasets permitted comparison of variables, both spatially and temporally (weekly intervals). Analyses were based on values centered on nine locations including Dallas, Texas (32.8° N; 96.8° W), Indianapolis, Indiana (39.8° N, 86.2° W), Lincoln, Nebraska (40.9° N; 96.7° W), Ottawa, Ontario (45.3° N; 75.6° W), Winnipeg, Manitoba (49.9° N; 97.14° W), Saskatoon, Saskatchewan (52.1° N, 106.6° W), Lethbridge, Alberta (49.7° N; 112.9° W), Peace River, Alberta (56.2° N, 117.3° W) and Fairbanks, Alaska (64.8° N, 147.7° W).

Contour maps were generated by importing EI values into geographic information system software, ArcView[®] 8.1¹ (ESRI Inc. 2001). Final EI values were displayed in the four categories defined above: 'Unfavourable', 'Suitable'; 'Favourable'; and 'Very Favourable'.

Table 1. CLIMEX[®] parameter values used to predict potential distribution and relative abundance of *Fusarium graminearum* (Fg), *Kochia scoparia* (Ks) and *Oulema melanopus* (Om) in North America.

CLIMEX[®] Growth Parameters:		Fg	Ks	Om
Temperature				
DV0	Lower optimal average weekly minimum temperature (°C)	9.0	9.0	6.5
DV1	Lower optimal average weekly maximum temperature (°C)	15.0	18.0	7.0
DV2	Upper optimal average weekly maximum temperature (°C)	25.0	32.0	26.0
DV3	Limiting high average weekly maximum temperature (°C)	35.0	40.0	35.0
Moisture				
SM0	Limiting low soil moisture	0.20	0.08	0.02
SM1	Lower optimal soil moisture	0.45	0.12	0.10
SM2	Upper optimal soil moisture	1.50	0.35	1.00
SM3	Limiting high soil moisture	2.00	1.30	1.50

Diapause				
DPD0	Diapause induction day length (hours)	not used	not used	14.00
DPT0	Diapause induction temperature (average weekly minimum) (°C)	not used	not used	11.00
DPD1	Diapause termination temperature (average weekly minimum) (°C)	not used	not used	6.00
DPD	Diapause development (days)	not used	not used	120.00
DPSW	Summer or winter diapause	not used	not used	0.00
Light				
LT0	Daylength above which growth is maximum (hours)	not used	11.75	not used
LT1	Daylength below which growth is zero (hours)	not used	16.00	not used
CLIMEX[®] Stress Parameters:				
Cold Stress				
TTCS	Cold stress threshold (average weekly minimum temperature) (°C)	not used	-12.0	-20.0
THCS	Rate of cold stress accumulation	not used	0.0004	0.0015
Heat Stress				
TTHS	Heat stress threshold (mean weekly maximum temperature) (°C)	not used	40.0	35.0
THHS	Rate of heat stress accumulation	not used	0.008	0.005
Dry Stress				
SMDS	Dry stress threshold (mean weekly minimum soil moisture)	not used	0.02	0.02
HDS	Rate of dry stress accumulation	not used	-0.003	-0.1
Wet Stress				
SMWS	Wet stress threshold (mean weekly maximum soil moisture)	not used	2.0	1.5
HWS	Rate of wet stress accumulation	not used	0.001	0.0005
Degree-Days				
PDD	Degree-days per generation	300	825	not used

Results and discussion

Kochia is associated with continental climates and is most abundant in regions of North America with warm, dry growing seasons (Figure 1A) (Leeson and Beckie 2012, this volume). Application of the NCAR273 CCSM scenario to the bioclimate model for kochia (Beckie et al. 2012, this volume) resulted in increased range and relative abundance across North America for this species. The range expanded north and west to include most of the Northern Great Plains (Figure 1D). The other two GCMs, CSIRO Mark 3.0 (Figure 1B) and MIROC-H (Figure 1C), resulted in similar shifts across Canada; however both GCMs predicted a significant range contraction in southern United States (Figure 1). Compared to current climate (CRU), the percent area of North America with $EI \geq 15$ was predicted to increase for each of the GCM scenarios. For current climate, the bioclimatic model indicated that 8% of the area would have $EI \geq 15$, compared with 16%, 17%, and 18% for CSIRO Mark 3.0, MIROC-H and NCAR273 CCSM, respectively. The NCAR273 CCSM climate resulted in higher EI values across northern regions of the Great Plains. At Peace River in northern Alberta, EI values were 0, 15.5, 19 and 21.9 for CRU, CSIRO Mark 3.0, MIROC-H and NCAR273 CCSM, respectively (Table 2). Increases in EI were associated with increased TI and GI weeks positive and decreased CS. In more central locations of North America, MIROC-H resulted in the highest EI values, primarily due to increased TI and MI. For example, MIROC-H predicted $EI = 24.8$ ($TI = 39.8$; $MI = 94.3$) at Winnipeg, Manitoba, compared to $EI = 12.8$ ($TI = 29.5$; $MI = 91.1$) for current climate (CRU). Further south, at Lincoln, Nebraska, GCM inputs resulted in reduced EI values, although CSIRO Mark 3.0 predictions ($EI = 20.5$) were not significantly different from CRU ($EI = 20.6$). Overall, these results were similar to the bioclimate analyses using incremental scenarios. Beckie et al. (2012b, this volume) reported that incremental temperature increases of 1 to 3 °C (unchanged precipitation) would result in range expansion of kochia within Canada into the interior of British Columbia, the northern Prairies (including the Peace River region of Alberta), northern Ontario, and to a lesser extent, parts of southern Québec and the United States. Kochia was also predicted to expand eastward into the mid-west of the continent and into Atlantic regions. Beckie et al. (2012, this volume) also conducted a sensitivity analysis using the bioclimate model for kochia and found that the main factor limiting the northern range expansion of the species in Canada is the length of the growing season (or accumulated growing degree-days) required to complete one generation. Further, they found that increased precipitation had the potential to mollify the influence of warmer temperatures on the range expansion of the species. An increase of 20% above normal precipitation curtailed population expansion of this drought-tolerant weed into eastern North America. Alternatively, 20% less than normal precipitation intensified the effect of increasing temperatures due to the fact that the species is best adapted to warm, dry climates. In summary, potential range

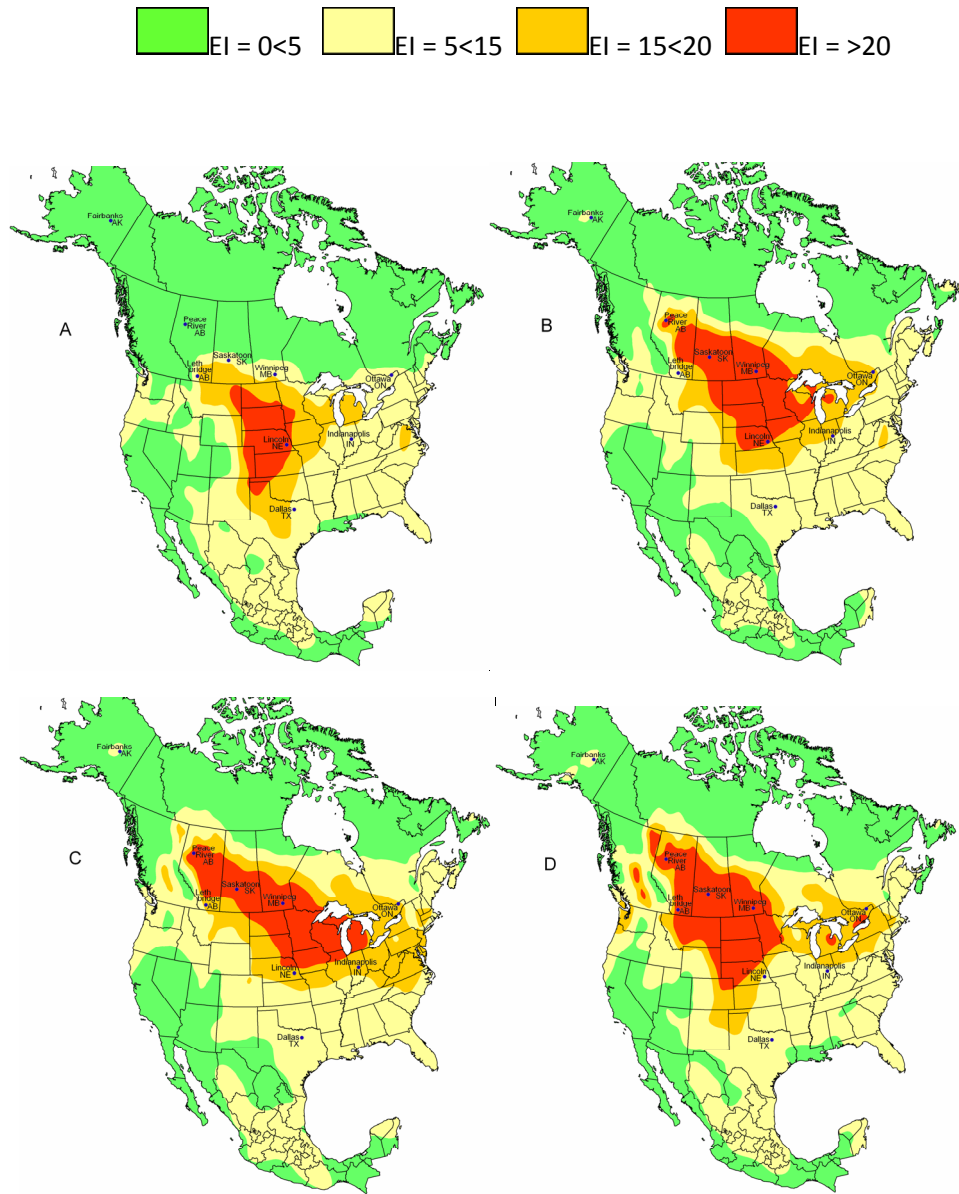


Figure 1. Predicted distribution and relative abundance of *Kochia scoparia* in North America, based on Ecoclimatic Indices (EI) for: current climate (A); and for CSIRO Mark 3.0 (B); MIROC-H (C); NCAR273 CCSM (D) general circulation models.

Table 2. Baseline (CRU) and general circulation model (CSIRO Mark 3.0, MIROC-H, NCAR273 CCSM) scenarios and resulting Ecoclimatic Index (EI), temperature (TI), moisture (MI), diapause (DI), growth index (GI), number of weeks GI was positive (Weeks GI +) and cold stress (CS), for *Kochia scoparia* at nine locations in North America.

Location	Scenario	EI	TI	MI	GI	Weeks	
						GI +	CS
Fairbanks, AK	CRU	0.0	10.2	79.7	9.8	17.8	133.2
	CSIRO Mark 3.0	2.4	18.8	79.4	17.8	19.8	53.6
	MIROC-H	3.3	19.8	79.5	18.6	20.3	63.7
	NCAR273 CCSM	4.6	19.6	81.7	18.7	20.6	30.2
Peace River, AB	CRU	0.0	17.8	95.7	15.3	23.9	50.0
	CSIRO Mark 3.0	15.5	26.4	95.2	22.4	25.0	8.2
	MIROC-H	19.0	28.9	93.9	24.6	26.0	11.9
	NCAR273 CCSM	21.9	30.3	92.3	23.9	25.2	3.8
Saskatoon, SK	CRU	8.9	25.8	99.3	21.4	24.2	41.0
	CSIRO Mark 3.0	24.6	34.1	94.4	25.3	24.4	2.7
	MIROC	23.2	36.2	92.8	25.6	25.2	9.1
	NCAR273 CCSM	27.2	35.9	98.2	28.2	25.3	3.3
Lethbridge, AB	CRU	10.9	24.2	81.1	16.2	24.4	9.5
	CSIRO Mark 3.0	12.4	31.6	65.7	13.8	20.3	0.1
	MIROC-H	14.7	34.3	69.9	16.3	23.7	0.5
	NCAR273 CCSM	21.8	34.4	81.7	22.6	26.2	0.1
Winnipeg, MB	CRU	12.8	29.5	91.1	22.0	24.3	38.9
	CSIRO Mark 3.0	26.4	38.0	89.3	26.7	25.0	1.5
	MIROC-H	24.8	39.8	94.3	27.9	26.8	10.9
	NCAR273 CCSM	24.3	37.3	83.1	25.6	25.4	5.0
Ottawa, ON	CRU	8.3	30.7	28.5	9.6	24.7	11.4
	CSIRO Mark 3.0	14.9	39.6	34.7	14.9	25.9	0.2
	MIROC-H	14.7	41.8	37.5	15.0	27.5	2.0
	NCAR273 CCSM	16.6	40.2	35.4	16.7	26.3	0.9
Indianapolis, IN	CRU	13.5	47.8	46.8	13.5	28.6	0.0
	CSIRO Mark 3.0	15.2	52.7	52.9	15.2	28.8	0.0
	MIROC-H	17.3	54.8	60.4	17.3	28.9	0.0
	NCAR273 CCSM	13.9	52.2	40.7	13.9	27.3	0.0
Lincoln, NE	CRU	20.6	46.4	90.5	20.7	28.5	0.4
	CSIRO Mark 3.0	20.5	49.3	92.4	20.5	28.7	0.0
	MIROC-H	18.6	46.8	93.8	18.6	28.9	0.0
	NCAR273 CCSM	15.4	49.0	83.9	15.4	28.0	0.0
Dallas, TX	CRU	13.1	64.8	71.4	13.1	29.4	0.0
	CSIRO Mark 3.0	9.7	56.9	82.7	9.7	29.6	0.0
	MIROC-H	8.4	55.5	76.5	8.5	28.1	0.0
	NCAR273 CCSM	8.1	63.9	63.6	8.1	25.4	0.0

expansion of kochia into different regions of North America under a warming climate will be closely linked to how precipitation distribution and abundance are altered from current patterns. The GCMs predicted warmer temperatures, resulting in longer, warmer growing seasons. Longer growing seasons would result in both range extension and potential for higher weed densities.

Fusarium graminearum is commonly isolated from cereal heads and kernels in Manitoba (Clear and Patrick 2010; Tekauz et al. 2000), and first started to become more common in south east Saskatchewan in the late 1990's and other regions in the 2000's (Clear and Patrick 2010), while in Alberta it is being detected with increasing frequency in the southern regions of the province (Clear and Patrick 2010). The appearance of low levels of *F. graminearum* in Alberta has raised concerns regarding the potential long-term development and impact of FHB in the western Prairie ecoregion. Application of the GCMs to the bioclimate model for *F. graminearum* (Turkington et al. 2011) predicted somewhat more variability in area suitability than in distribution (range shifts), as a result of climate change (Figure 2). Under current climate (CRU), the bioclimatic model suggested that 20% of North America was deemed as having climate suitable for *F. graminearum*, especially those areas where most small grain cereals, such as wheat, are produced (Foreign Agricultural Service 2004; National Agricultural Statistics Service 2008). Application of the three GCMs predicted that this value would increase to 26, 28 and 32% of North America for CSIRO Mark 3.0, MIROC-H, and NCAR273 CCSM, respectively. NCAR273 CCSM resulted in the highest EI value for all locations except Ottawa, Ontario (Table 3). Depending on the GCM, central and southern locations in North America had lower EI values that were associated with decreased TI, MI and GI values (Table 3), which likely resulted from temperatures exceeding the upper thresholds of the CLIMEX model, with lower MI values (drier conditions) due to reduced rainfall and higher rates of evapotranspiration. An understanding of the potential long-term distribution and severity of FHB caused by *F. graminearum* is critical for developing appropriate monitoring programs and management strategies, especially in those regions where this pathogen is currently found infrequently and where environmental conditions appear to be conducive to FHB development. In North America, the highest EI values tended to occur in the eastern half of the continent, delimited in the west by the Red River region of Manitoba, North Dakota and Minnesota (Figure 2). Sensitivity analysis demonstrated that changes in CLIMEX[®] derived EI values for *F. graminearum* were more sensitive to changes in soil moisture than temperature (Turkington et al. 2011). Studies in small grain cereals have shown that moisture seems to be the most important environmental factor influencing the severity of infection caused by *F. graminearum* (Stack 1997; McMullen et al. 1997a, 1997b; Tekauz et al. 2000). As a result, variation in summer rainfall can have a substantial impact on FHB development. For example, Turkington et al. (2011) reported that a potential expansion and greater seasonal development of FHB may occur in areas of the

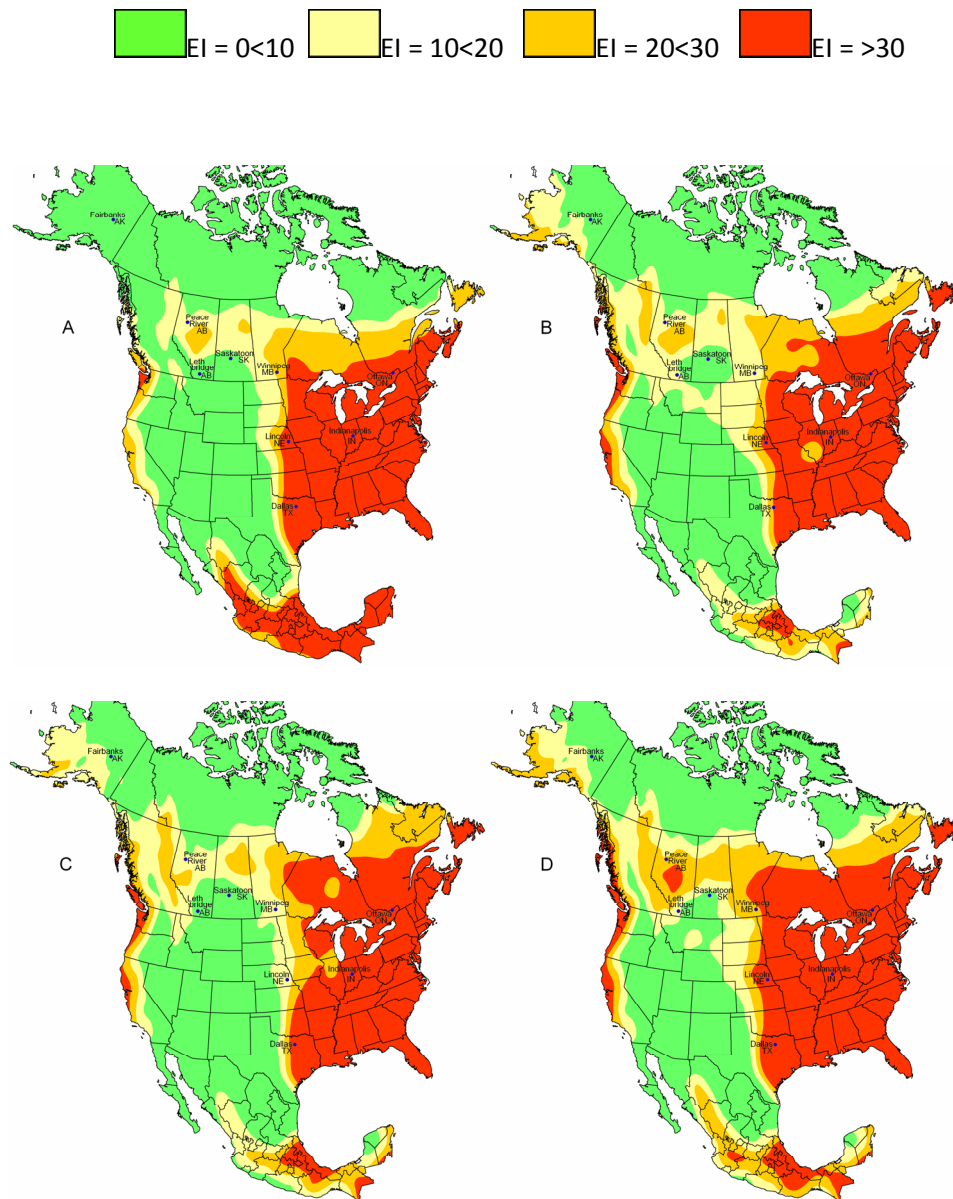


Figure 2. Predicted distribution and relative abundance of *Fusarium graminearum* in North America, based on Ecoclimatic Indices (EI) for: current climate (A); and for CSIRO Mark 3.0 (B); MIROC-H (C); NCAR273 CCSM (D) general circulation models.

western Prairie ecoregion with above-average rainfall (130% of normal) during the growing season. This is consistent with observations in south eastern Saskatchewan where FHB caused by *F. graminearum* increased in prevalence from the mid to late 1990s into 2000 and 2001 (Clear and Patrick 2000, 2010), a period with above average precipitation.

Cereal leaf beetle occurs over most regions of cereal production across North America. Under current climate conditions (CRU), the model predicted that 17% of North America would have $EI \geq 20$, whereas CSIRO Mark 3.0, MIROC-H and NCAR273 CCSM scenarios predicted that 32%, 31% and 35% of North America would have $EI \geq 20$, respectively. Across North America, EI values were constrained by growing season factors (TI, MI, DI, GI) and stress (CS and HS). Accumulated stress values of greater than 100 indicates stress levels are sufficient to limit the species from persisting. Olfert and Weiss (2006) reported that under current climate conditions, CS values were greater than 100 at Fort Smith, Northwest Territories, which indicated that cereal leaf beetle would not survive winters north of 60 °N latitude. Under current climate (CRU), results indicated that northern distribution of cereal leaf beetle would be limited by CS. For example, CRU predicted EI values at Fairbanks, Alaska were limited by a lethal $CS = 135.7$ (Table 4). Under climate change, the CSIRO Mark 3.0 scenario predicted $CS = 11.6$ at Fairbanks, a value that was lower than Saskatoon, Saskatchewan under current climate conditions ($CS = 12.8$). For regions in the Northern Great Plains, GCM scenarios predicted increased EI values resulting from increased TI and number of weeks GI positive. Ecoclimatic Index values near Ottawa, Ontario, were predicted to increase from $EI = 23.7$, under current climate (CRU), to $EI = 31.2$ by NCAR273 CCSM. This increase was attributed to a warmer, longer growing season. Future climate was predicted to result in increased rates of HS accumulation in the Southern Great Plains. At Dallas, Texas, EI was predicted to decrease from 23.3 (CRU) to 0 by the MIROC-H scenario, suggesting that the species could not persist in this region under those conditions. This decrease in EI was related to lethal accumulation of HS for both climates predicted by the CSIRO Mark 3.0 and MIROC-H scenarios. Overall, the three GCM's (Figures 3B, C, D) predicted a significant shift west and north in the potential distribution and abundance of cereal leaf beetle, relative to CRU (Figure 3A). This is similar to results reported by Olfert and Weiss (2006) where, compared to current climate conditions, incremental increases in average temperatures predicted an increase in both range and relative abundance of cereal leaf beetle. Further, they reported that under current climate conditions, 13.2% of Canada would be expected to have $EI \geq 20$, and that an increase of 3 °C in average temperature was predicted to result in an increase to 36.3% of the modeled area of Canada. Haynes and Gage (1981) speculated that expansion to the Great Plains may be limited by a lack of suitable overwintering sites and high soil temperatures at the time of pupation. High soil temperatures

resulting from climate change may be an important limiting factor. In Saskatchewan, mid-summer soil temperatures (2.5 cm depth) can exceed 40 °C (O Olfert, unpublished data); these temperatures exceed the upper optimum temperature threshold (DV3 = 35 °C). Further, Olfert and Weiss (2006) noted that their model was sensitive to soil moisture conditions and that this agreed with observations showing that adequate soil moisture is critical to larvae (when they drop to the soil) and pupae (Karren 1986). This factor will also influence the potential impact of climate change under GCM scenarios.

Table 3. Baseline (CRU) and general circulation model (CSIRO, MIROC-H, NCAR273 CCSM) scenarios and resulting Ecoclimatic Index (EI), temperature (TI), moisture (MI), growth index (GI), and number of weeks GI was positive (Weeks GI +), for *Fusarium graminearum* at nine locations in North America.

Location	Scenario	EI	TI	MI	GI	Weeks GI +
Fairbanks, AK	CRU	1.4	14.3	24.1	3.3	11.8
	CSIRO Mark 3.0	5.0	23.5	25.8	6.0	12.4
	MIROC-H	6.4	25.0	32.3	7.5	13.6
	NCAR273 CCSM	6.8	24.2	33.8	7.7	15.7
Peace River, AB	CRU	14.6	26.1	58.5	14.8	24.3
	CSIRO Mark 3.0	15.2	33.1	56.7	15.2	25.8
	MIROC-H	14.1	36.1	60.1	14.1	27.4
	NCAR273 CCSM	23.0	36.6	67.1	23.0	27.1
Saskatoon, SK	CRU	8.6	32.9	29.3	8.6	19.9
	CSIRO Mark 3.0	6.7	35.3	36.1	6.7	17.5
	MIROC-H	4.9	35.1	27.5	4.9	15.2
	NCAR273 CCSM	11.5	35.7	37.1	11.5	22.2
Lethbridge, AB	CRU	5.3	29.7	36.8	6.5	15.2
	CSIRO Mark 3.0	9.6	31.1	42.2	10.1	14.5
	MIROC-H	6.0	31.3	31.9	6.3	14.3
	NCAR273 CCSM	11.6	32.1	39.8	11.9	18.5
Winnipeg, MB	CRU	22.8	34.2	71.3	22.8	26.1
	CSIRO Mark 3.0	15.9	34.1	63.9	15.9	22.1
	MIROC-H	13.7	34.2	48.4	13.7	21.9
	NCAR273 CCSM	24.7	32.9	80.9	24.7	26.8
Ottawa, ON	CRU	36.0	36.3	99.7	36.0	27.3
	CSIRO Mark 3.0	35.6	38.2	95.4	35.6	30.1
	MIROC-H	37.4	39.6	96.2	37.4	32.4
	NCAR273 CCSM	35.8	37.4	96.7	35.8	30.4
Indianapolis, IN	CRU	37.9	39.2	97.7	37.9	41.2
	CSIRO Mark 3.0	22.8	30.2	78.8	22.8	36.2

	MIROC-H	24.8	31.0	71.7	24.8	35.2
	NCAR273 CCSM	30.1	30.5	92.2	30.1	35.5
Lincoln, NE	CRU	26.9	34.7	61.4	26.9	32.0
	CSIRO Mark 3.0	19.9	26.8	55.0	19.9	26.5
	MIROC-H	13.2	26.7	27.6	13.2	19.3
	NCAR273 CCSM	23.2	28.9	64.6	23.2	27.5
Dallas, TX	CRU	31.4	39.6	65.6	31.4	38.0
	CSIRO Mark 3.0	21.5	36.6	46.0	21.5	25.2
	MIROC-H	24.0	35.1	42.7	24.0	26.6
	NCAR273 CCSM	32.7	40.9	68.2	32.7	32.4

Table 4. Baseline (CRU) and general circulation model (CSIRO Mark 3.0, MIROC-H, NCAR273 CCSM) scenarios and resulting Ecoclimatic Index (EI), temperature (TI), moisture (MI), diapause (DI), growth index (GI), number of weeks GI was positive (Weeks GI +), heat stress (HS), cold stress (CS), and dry stress (DS), for *Oulema melanopus* at nine locations in North America.

Location	Scenario	EI	TI	MI	DI	GI	Weeks		HS	CS	DS
							GI +				
Fairbanks AK	CRU	1.6	36.7	90.7	17.8	17.8	9.2	0.0	0.0	7	1.1
	CSIRO									135.	
	Mark 3.0	22.2	40.3	90.7	25.6	25.6	13.2	0.0	11.6	1.2	
	MIROC-H	23.9	41.4	91.7	28.4	28.4	14.6	0.0	16.1	1.0	
	NCAR273 CCSM	26.1	41.8	92.5	27.1	27.1	14.0	0.0	2.5	1.1	
Peace River AB	CRU	15.4	51.0	99.9	18.2	18.2	9.5	0.0	16.6	0.0	
	CSIRO										
	Mark 3.0	27.4	55.0	99.8	27.4	27.4	14.2	0.0	0.0	0.0	
	MIROC-H	29.0	57.3	99.8	29.0	29.0	15.0	0.0	0.0	0.0	
	NCAR273 CCSM	28.5	55.6	99.7	28.6	28.5	14.8	0.0	0.0	0.0	
Saskatoon SK	CRU	21.2	52.9	100.	24.1	24.1	12.5	0.0	12.8	0.0	
	CSIRO										
	Mark 3.0	26.3	54.9	99.3	28.4	26.3	14.7	0.0	0.0	0.0	
	MIROC-H	26.2	56.4	98.9	30.0	26.2	15.5	0.0	0.0	0.0	
	NCAR273 CCSM	28.2	54.0	100.	30.4	28.2	15.7	0.0	0.0	0.0	
Lethbridge AB	CRU	15.2	55.0	95.6	15.8	15.2	8.2	0.0	0.0	0.0	
	CSIRO										
	Mark 3.0	17.8	57.1	88.0	24.2	17.8	12.6	0.0	0.0	0.0	
	MIROC-H	17.5	59.9	91.5	24.3	17.5	12.6	0.0	0.0	0.0	
	NCAR273	22.1	57.0	95.1	26.6	22.1	13.8	0.0	0.0	0.0	

		CCSM									
Winnipeg MB	CRU	21.8	53.4	100.	0	25.6	25.3	13.3	0.0	13.9	0.0
	CSIRO			100.							
	Mark 3.0	28.5	53.3	0	33.0	28.5	17.0	0.0	0.0	0.0	
	MIROC-H NCAR273	28.1	56.1	0	34.1	28.1	17.6	0.0	0.0	0.0	
Ottawa ON	CCSM	28.7	52.6	99.7	33.3	28.7	17.1	0.0	0.0	0.0	
	CRU	23.7	57.5	77.4	26.3	23.8	13.6	0.0	0.5	0.0	
	CSIRO										
	Mark 3.0	30.0	59.4	77.3	35.1	30.0	18.2	0.0	0.0	0.0	
Indianapolis IN	MIROC-H NCAR273	30.9	63.7	79.3	36.8	30.9	19.1	0.0	0.0	0.0	
	CCSM	31.2	59.6	78.4	36.0	31.2	18.7	0.0	0.0	0.0	
	CRU	29.8	66.1	85.3	41.4	29.8	21.7	0.0	0.0	0.0	
	CSIRO										
Lincoln NE	Mark 3.0	26.1	62.6	84.3	50.2	26.1	25.9	0.1	0.0	0.0	
	MIROC-H NCAR273	25.8	62.1	90.6	52.0	25.9	26.4	0.7	0.0	0.0	
	CCSM	22.6	60.5	81.0	49.2	22.6	25.6	0.0	0.0	0.0	
	CRU	28.1	61.2	100.	0	38.3	28.1	19.9	0.0	0.0	0.0
Dallas TX	CSIRO										
	Mark 3.0	24.3	58.4	99.9	45.8	24.5	22.7	1.2	0.0	0.0	
	MIROC-H NCAR273	15.2	55.5	99.7	47.8	19.6	18.6	25.5	0.0	0.0	
	CCSM	22.6	58.0	97.5	45.3	22.9	22.2	1.6	0.0	0.0	
Dallas TX	CRU	23.3	71.6	91.3	51.8	23.8	24.7	2.3	0.0	0.0	
	CSIRO							122.			
	Mark 3.0	1.5	58.3	97.3	25.5	9.2	8.1	8	0.0	0.0	
	MIROC-H NCAR273	0.0	54.5	94.4	17.6	5.6	5.0	0	0.0	0.0	
	CCSM	2.2	61.8	86.2	20.8	7.1	7.4	58.8	0.0	0.0	

Compared to predicted range and distribution under current climate conditions, model results indicated that all three crop pests would have increases in range and relative abundance under the three general circulation model scenarios. These changes were most prevalent in northern regions of North America. Conversely, model output predicted that the range and relative abundance of these crop pests could contract in regions where climate conditions became limiting due to warmer, drier climates. Though responses were specific to species, location and GCM, there were general similarities among the three species. Notable changes of

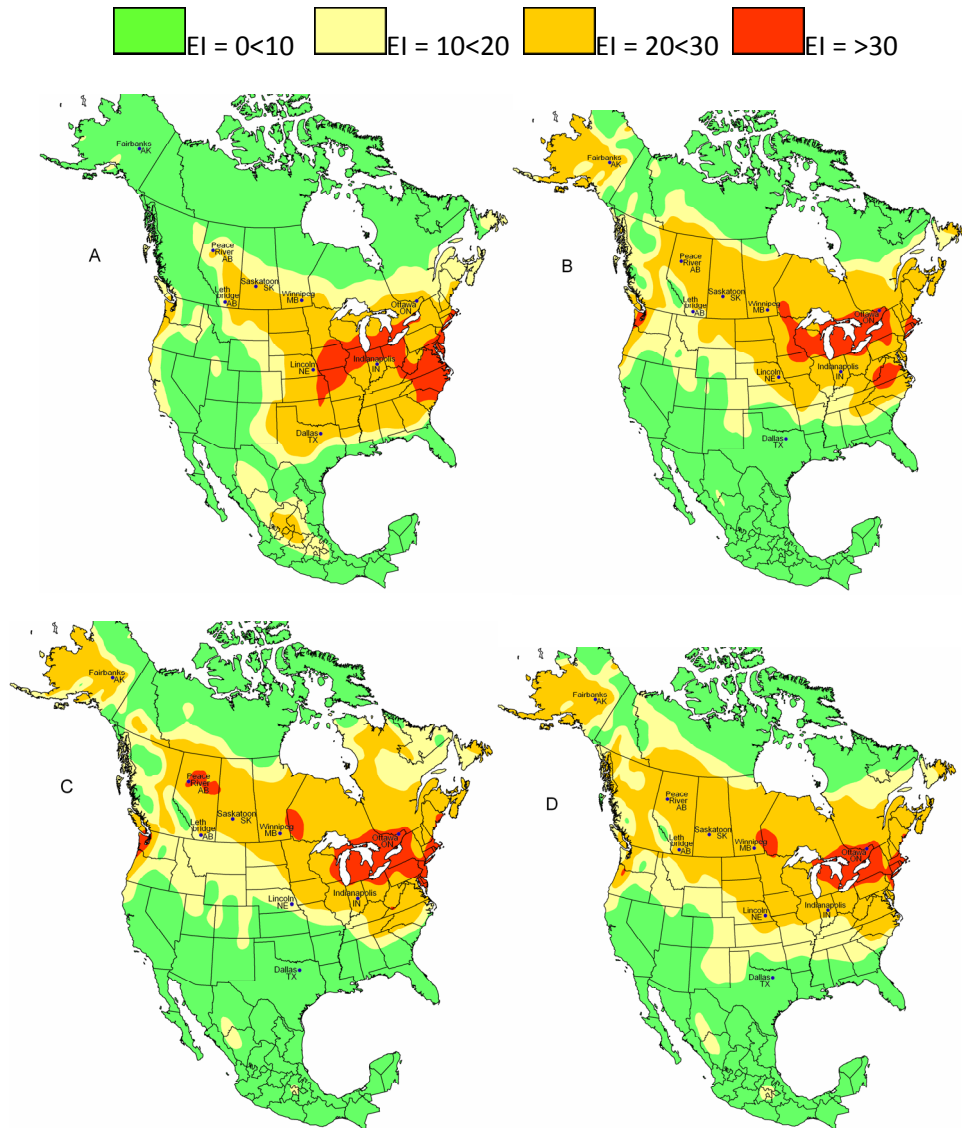


Figure 3: Predicted distribution and relative abundance of *Oulema melanopus* in North America, based on Ecoclimatic Indices (EI) for: current climate (A); and for CSIRO Mark 3.0 (B); MIROC-H (C); NCAR273 CCSM (D) general circulation models.

were predicted to occur across the Canadian prairies. The CSIRO Mark 3.0 and MIROC-H scenarios predicted increased pest status (crop risk) across the northern areas of Alberta, Saskatchewan and Manitoba, with southern areas of the prairies predicted to have conditions similar to concurrent climate. The NCAR273 CCSM scenario predicted a significant increase in pest status, particularly regions north 49 °N latitude for all three species. Under current climate conditions (CRU), pest risk (EI) at Peace River, Alberta, was categorized as 'unfavourable' for kochia, but 'suitable' for *F. graminearum* and cereal leaf beetle. Climate change scenarios predicted that pest risk at Peace River, Alberta, would increase to 'favourable' for *F. graminearum* and cereal leaf beetle and to 'very favourable' for kochia. At Saskatoon, Saskatchewan, EI values under climate change suggested that conditions would be 'very favourable' for kochia, 'favourable' for cereal leaf beetle and 'suitable' for *F. graminearum*. Results demonstrate the importance of investigating mitigation strategies at a regional level that will assist the agricultural sector with managing pest species in future climates.

Mika et al. (2008) suggested that rather than using incremental temperature and moisture scenarios for estimating impact of climate change on species distribution and abundance, the widely accepted and more commonly used GCMs should be used in conjunction with bioclimate models. When compared to studies that were based on incremental scenarios (Olfert and Weiss 2006; Beckie et al. 2012, this volume) results from this study suggest that output from the two approaches were similar. Similar findings were also reported for the migratory grasshopper, *Melanoplus sanguinipes* (Fab.), where model predictions were not significantly different for both incremental scenarios and GCMs (Olfert et al. 2011). Both approaches can be seen as two different methods of sensitivity analysis and are complementary approaches for studying potential impacts of future climate on species distribution and abundance.

In conclusion, crop growers must consider a number of factors that limit crop production including biotic and abiotic factors. Producers frequently are required to make production decisions based on the potential impact of multiple pest species, including weeds, plant diseases and insects. Bioclimatic models have proven useful for studies investigating the potential impact of climate on insect, weed and pathogen populations associated with cultivated crops. Our multiple species comparisons of responses of pests to climate change have permitted analysis of responses of crop pests across North America. In addition, geographic regions that are likely to be at greatest risk of invasion or of enhanced seasonal development from climate change-sensitive species can be identified. By providing advanced notification of the potential invasiveness of specific crop pests as a result of a changing climate, those involved in integrated crop management research will have a wide window of opportunity to develop and transfer management tactics to mitigate population expansion of these species. Through increased awareness, growers or land managers in potentially high-risk areas can be more proactive in

monitoring or detection, and will have useful information, when needed, on recommended practices to combat the establishment or spread of these pest species.

Acknowledgements

D. Giffen is gratefully acknowledged for preparation of the maps.

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Influence of climate on weed species distribution in the Canadian Prairies

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Weed surveys conducted in the Canadian Prairie provinces (Alberta, Saskatchewan, Manitoba) indicate that weeds are often associated with distinct regions. The influence of climate on the distribution of weed species in the Prairies was determined using weed survey data from the 1970s to 2000s. During this period, over 17,800 fields located throughout the Prairie agricultural area were surveyed. Redundancy analysis was used to determine the association of the 60 most common weed species with climatic factors. Growing season temperature (degree-days) is the main climatic factor determining weed species distribution. Species positively associated with warm growing seasons include Russian thistle (*Salsola tragus* L.), kochia [*Kochia scoparia* (L.) Schrad.], and redroot pigweed (*Amaranthus retroflexus* L.). Additionally, kochia and Russian thistle are associated with extended growing seasons. An increase in average temperatures may have facilitated the northward expansion of these species. Hemp-nettle (*Galeopsis tetrahit* L.), field horsetail (*Equisetum arvense* L.), and perennial sow-thistle (*Sonchus arvensis* L.) are associated with high annual rainfall. Change in precipitation patterns may be expected to influence the distribution of these species. Over half of the 60 most common weed species had more than 20% of the variance in their distribution associated with climate. Thus, climate change is expected to alter the distribution and abundance of many of the common weed species in the Prairies.

Additional keywords: climate change, growing degree-days, precipitation, weed distribution maps, weed surveys

Introduction

Climate is the main factor determining vegetation distribution and abundance (Sutherst 2000; Woodward and Williams 1987). As a consequence of increasing atmospheric levels of greenhouse gases, global annual mean temperature is predicted to rise by 1.5 to 4 C by the end of the century (Patterson 1995; Quarles 2007). However, precipitation patterns across North America are expected to be

more stochastic and less predictable than temperature patterns (Gitay et al. 2002). Climate change is expected to alter the geographic range of agricultural weeds (Fuhrer 2003; Patterson 1995). For example, global warming may result in range expansion of weed species into higher latitudes of the northern hemisphere (McDonald et al. 2009). The northern limit of warm-temperate annual species is set primarily by the heat units (degree-days) accumulated during the growing season (Patterson et al. 1999).

Weed surveys conducted in the Prairie provinces indicate that weed species are often associated with particular regions (Leeson et al. 2005). These distributions may change due to invasion, regional adoption of farming practices, and yearly fluctuations in weather. However, underlying patterns may indicate that climate and/or soils are restricting the spread of weed species.

Will the range of agricultural weed species be impacted by climate change? There is little information in the literature on this subject. It would be informative to identify those weed species whose distribution may be most affected by a warming climate with variable precipitation. Identification of climate change-sensitive species would help target future financial and human resources to develop best management practices to mitigate their population expansion or invasiveness. In this paper we determine which Prairie weed species currently have distributions correlated with climatic factors, and thereby most likely to be affected by climate change.

Materials and methods

Data sources

Weed distribution data originated from field surveys conducted between 1973 and 2003 in the three Prairie provinces – Alberta, Saskatchewan, and Manitoba (Leeson et al. 2005). During this period, each of the provinces was surveyed four times, once per decade. Fields surveyed were primarily spring-planted cereal, oilseed and pulse crops, although some fall rye (*Secale cereale* L.) and winter wheat (*Triticum aestivum* L.) fields were also included. Data from a total of 17,869 fields were included in the analysis.

For each survey, a stratified sampling procedure was used to select fields representative of the agricultural area in each province. The area can be divided into ecoregions and ecodistricts. Ecoregions are areas of similar climate, natural vegetation, soils, and land use (Ecological Stratification Working Group 1995). Each ecoregion consists of one or more ecodistricts. Ecodistricts are similar in landform, relief, surficial material, soil, vegetation, and land use. The fields were located in 209 ecodistricts (Figure 1).

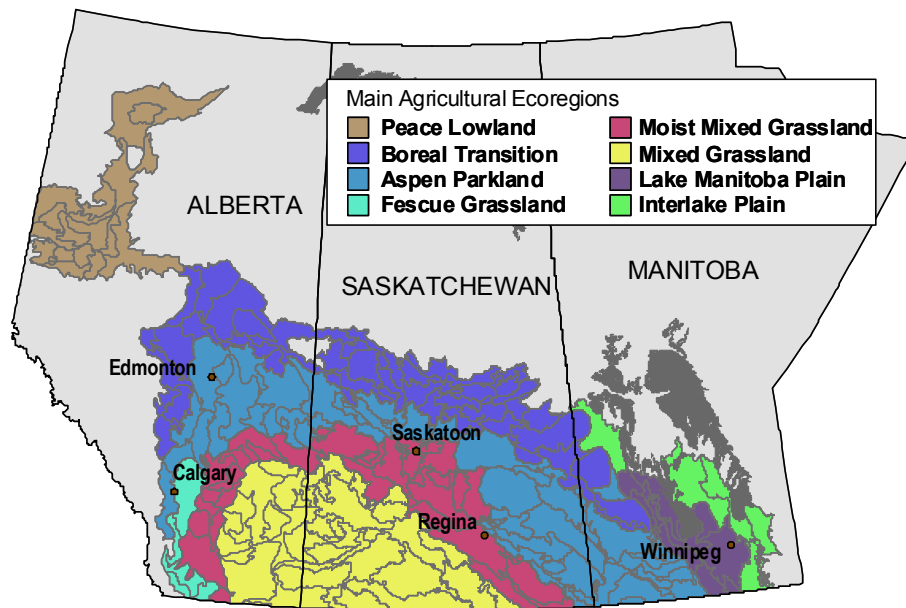


Figure 1. Ecodistricts included in the study and main agricultural ecoregions. Ecoregions with few surveyed ecodistricts are grouped with adjacent ecoregions.

Climate data for each ecodistrict was based on climate normals for the years 1961 to 1990 (Agriculture and Agri-Food Canada 1997). Five climatic variables were investigated: growing season length, growing degree-days, precipitation surplus, annual rainfall, and annual snowfall (Figure 2). Growing season length is based on the first and last day when mean daily air temperature equals or exceeds 5 C. Growing degree-days is the sum of degrees that the mean daily air temperatures are above a base temperature of 10 C. Precipitation surplus is the total precipitation minus annual potential evapotranspiration calculated using the Penman method (Penman and Schofield 1951). Annual rainfall and annual snowfall is average total precipitation in the form of rain and snow, respectively.

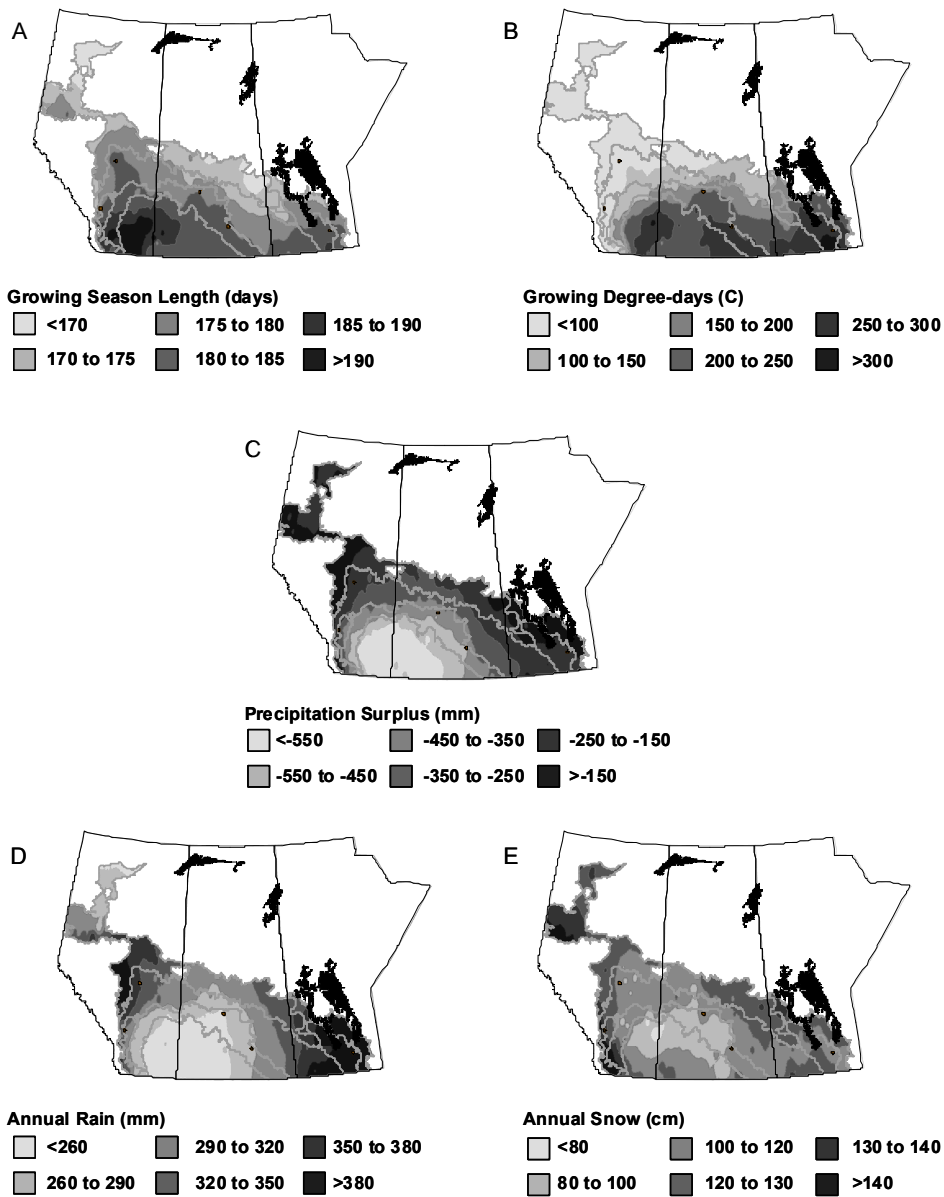


Figure 2. Climatic variables included in the analysis: (A) growing season length, (B) growing degree-days, (C) precipitation surplus, (D) annual rainfall, and (E) annual snowfall.

Analysis

The association of weed species with climatic variables was examined by multivariate analysis using the program CANOCO (ter Braak and Šmilauer 2002). The 60 most common species in the survey were included in the analyses. Weed data were entered into the analysis as the square root of the frequency of each species within each of the ecodistricts. The climatic variables were used to constrain the analyses of the weed data, such that only variance attributable to these factors of interest was investigated. Constrained analyses allow direct associations to be made between the weed and climatic data.

Partial detrended canonical correspondence analyses (DCCA) resulted in a gradient length less than four standard deviations, indicating a linear response of species to the climatic variables (ter Braak and Šmilauer 2002). Therefore, subsequent analyses were based on redundancy analysis (RDA), a constrained form of principal components analysis. In this type of multivariate technique, weed species frequencies are constrained to be linear combinations of climatic variables.

The relative ability of each of the climatic variables to explain the variance in weed frequency was determined by conducting a series of partial constrained analyses (ter Braak and Šmilauer 2002). Partial analyses remove the variance in the weed data set attributable to a variable(s) by defining the variable(s) as covariables. Variance attributable solely to each climatic variable was determined by constraining the analysis by that variable and using the other four climatic variables as covariables. The explained variance may be entirely decomposed in this manner. The partitioned variance is expressed relative to the total variance explained by the factors of interest (Økland 1999).

Reduced model Monte Carlo permutation tests were conducted to determine whether the RDA axes explained more variance than expected by chance. For each Monte Carlo test, the climatic variables were randomly assigned to the weed data for each plot 1,999 times, and the analysis was re-run each time to determine the probability of a random version of the data explaining more variance than the original data.

To create a traditional RDA based on a correlation matrix, the species were centered, and the samples were neither centered nor standardized. Climatic data is quantitative; therefore, the ordinations were scaled to reflect the correlations emphasizing inter-species correlations, enabling the interpretation of correlations among climatic variables. Species scores were divided by standard deviation after the analysis was complete, thus reducing the influence of highly-variable species on the ordination.

The distributions of weeds with the strongest association with climate based on the RDA were mapped using ArcGIS 9.¹ Variable point kriging was used to map distributions of weeds based on the presence or absence of the weed in each of the surveyed fields.

Results and discussion

Association of weeds with climate

The climatic factors were highly correlated with each other (Table 1). Seven out of 26 possible interactions of the five factors were significant, accounting for 54.7% of the explained variance. Growing degree-days is the main climatic factor determining weed species distribution. While growing degree-days by itself accounted for 26.2% of the explained variance in weed distribution, it was also highly correlated with other climatic factors accounting for an additional 29.8%. Precipitation surplus accounted for a similar amount of variance, totalling 57.8%. These two factors accounted for most of the explained variance in the weed distributions (87.3%). The high degree of correlation between precipitation surplus and the other variables was expected, because it is a derived variable. Growing season length and annual rain accounted for slightly less of the variance, 41.0 and 34.7%, respectively. Annual snow only accounted for 16.9% of the variance.

Table 1. Percentage variance in weed frequency attributable to each of the climatic factors alone and the interaction of the factors (only significant interactions are shown).

Climatic factor	Percentage of explained variance
Growing degree-days	26.2
Precipitation surplus	6.4
Annual rain	5.6
Annual snow	4.4
Growing season length	2.8
Precipitation surplus and annual rain	12.9
Precipitation surplus and growing season length	8.0
Growing degree-days, precipitation surplus and growing season length	14.0
Growing degree-days, precipitation surplus and annual snow	3.6
Growing degree-days, growing season length and annual rain	3.3
Precipitation surplus, growing season length and annual rain	4.0
All five factors	8.9

Twenty-eight species had less than 20% of the variance in their distribution associated with climate (Table 2). These species tend to be widespread (Leeson et

al. 2005) and would not likely be affected by climate change. Some of these 28 species are relatively abundant (Leeson et al. 2005): wild oat (*Avena fatua* L.) ranked second, wild buckwheat (*Polygonum convolvulus* L.) ranked third, lamb's-quarters (*Chenopodium album* L.) ranked fifth, or are volunteers of widely-adapted crops (e.g., alfalfa (*Medicago sativa* L.), barley (*Hordeum vulgare* L.), wheat).

Relatively few species are associated with warm growing seasons (Figure 3). Russian thistle (*Salsola tragus* L.), kochia [*Kochia scoparia* (L.) Schrad.], and redroot pigweed (*Amaranthus retroflexus* L.), all C₄ species, are most strongly associated with a warm, dry climate. These weeds will likely increase in distribution and abundance as temperatures increase. However, if precipitation also increases beyond the species tolerance, abundance will decline. Wild mustard (*Sinapis arvensis* L.), green foxtail [*Setaria viridis* (L.) P. Beauv.], and barnyard grass [*Echinochloa* spp.] are most strongly correlated with warmer, wetter growing seasons. These weeds will also likely increase as temperatures increase. However, if precipitation also decreases beyond the species tolerance, then abundance will decline.

Most species examined are associated with a wetter, cooler climate. Hemp-nettle (*Galeopsis tetrahit* L.), field horsetail (*Equisetum arvense* L.), perennial sow-thistle (*Sonchus arvensis* L.) and narrow-leaved hawk's-beard (*Crepis tectorum* L.) have the strongest correlations with high annual rain and snow, precipitation surplus, and shorter, cooler growing seasons. These weeds will likely decrease as temperatures increase. If moisture is the limiting factor for these species, higher precipitation may allow these species to increase.

Table 2. Percentage of variance in weed distribution explained by the climatic factors on the first two axes of the redundancy analysis (RDA).

Weed species	Scientific name	Variance explained (%)
Russian thistle	<i>Salsola tragus</i> L.	66.4
Hemp-nettle	<i>Galeopsis tetrahit</i> L.	62.7
Kochia	<i>Kochia scoparia</i> (L.) Schrad.	60.6
Wild mustard	<i>Sinapis arvensis</i> L.	58.6
Green foxtail	<i>Setaria viridis</i> (L.) P. Beauv.	57.4
Field horsetail	<i>Equisetum arvense</i> L.	55.5
Redroot pigweed	<i>Amaranthus retroflexus</i> L.	55.4
Perennial sow-thistle	<i>Sonchus arvensis</i> L.	53.7
Annual smartweed	<i>Polygonum lapathifolium</i> L. and <i>P. scabrum</i> Moench	49.9

Weed species	Scientific name	Variance explained (%)
Narrow-leaved hawk's-beard	<i>Crepis tectorum</i> L.	46.6
Dandelion (includes red-seeded dandelion)	<i>Taraxacum officinale</i> Weber in F.H. Wigg. and <i>T. erythrospermum</i> Andr. ex Besser	46.0
Barnyard grass	<i>Echinochloa crusgalli</i> (L.) P. Beauv. and <i>E. microstachya</i> (Wiegand) Rydb.	45.9
Chickweed	<i>Stellaria media</i> (L.) Vill.	45.6
Night-flowering catchfly	<i>Silene noctiflora</i> L.	44.0
Flax	<i>Linum usitatissimum</i> L.	42.7
Flixweed	<i>Descurainia sophia</i> (L.) Webb ex Prantl	41.4
Shepherd's-purse	<i>Capsella bursa-pastoris</i> (L.) Medik.	39.3
Common groundsel	<i>Senecio vulgaris</i> L.	38.5
Stinkweed	<i>Thlaspi arvense</i> L.	38.3
Cow cockle	<i>Vaccaria hispanica</i> (Mill.) Rauschert	36.8
Pineappleweed	<i>Matricaria discoidea</i> D.C.	33.8
Quackgrass	<i>Elytrigia repens</i> (L.) Desv. ex B. D. Jacks	33.7
Canada thistle	<i>Cirsium arvense</i> (L.) Scop.	31.8
Cleavers (includes false cleavers)	<i>Galium aparine</i> L. and <i>G. spurium</i> L.	31.3
Thyme-leaved spurge (includes ridge-seeded spurge)	<i>Euphorbia serpyllifolia</i> Pers. and <i>E. glyptosperma</i> Engelm.	31.0
Broad-leaved plantain (includes narrow-leaved plantain)	<i>Plantago major</i> L. and <i>P. lanceolata</i> L.	29.4
Corn spurry	<i>Spergula arvensis</i> L.	27.0
Prostrate pigweed	<i>Amaranthus blitoides</i> S. Watson	24.7
Tumble pigweed	<i>Amaranthus albus</i> L.	24.3
Canola/Rapeseed	<i>Brassica napus</i> L. and <i>B. rapa</i> L.	23.8
Stork's-bill	<i>Erodium cicutarium</i> (L.) L'Hér. ex Aiton	23.2
Clover species	<i>Trifolium</i> spp. (<i>T. hybridum</i> L., <i>T. repens</i> L., <i>T. pratense</i> L.)	22.5
Round-leaved mallow	<i>Malva pusilla</i> Sm.	19.3
Lamb's-quarters (includes net-seeded lamb's-quarters)	<i>Chenopodium album</i> L. and <i>C. berlandieri</i> var. <i>zschackei</i> (Murr) Murr ex Asch.	18.8
American dragonhead	<i>Dracocephalum parviflorum</i> Nutt.	17.7
Black medic	<i>Medicago lupulina</i> L.	16.8
Foxtail barley	<i>Hordeum jubatum</i> L.	16.7

Weed species	Scientific name	Variance explained (%)
Ball mustard	<i>Neslia paniculata</i> (L.) Desv.	15.8
Bluebur (includes western bluebur)	<i>Lappula squarrosa</i> (Retz.) Dumort. and <i>L. occidentalis</i> (S. Watson) Greene	15.3
Wild buckwheat	<i>Polygonum convolvulus</i> L.	14.2
Tartary buckwheat (includes volunteer buckwheat)	<i>Fagopyrum tataricum</i> (L.) Gaertn. and <i>F. esculentum</i> Moench	14.0
Barley	<i>Hordeum vulgare</i> L.	12.8
White cockle	<i>Silene latifolia</i> Poir.	11.8
Dog mustard	<i>Erucastrum gallicum</i> (Willd.) O.E. Schultz	11.7
Wheat (includes durum)	<i>Triticum aestivum</i> L. and <i>T. durum</i> Desf.	10.2
Spiny annual sow-thistle (includes annual sow-thistle)	<i>Sonchus asper</i> (L.) Hill and <i>S. oleraceus</i> L.	9.6
Dock species	<i>Rumex</i> spp.	9.4
Vetch species	<i>Vicia</i> spp.	9.0
Persian darnel	<i>Lolium persicum</i> Boiss. & Hohen. ex Boiss.	8.8
Common pepper-grass (includes field pepper-grass)	<i>Lepidium densiflorum</i> Schrad. and <i>L. campestre</i> (L.) R. Br. in W.T. Aiton	8.5
Spear-leaved goosefoot	<i>Monolepis nuttalliana</i> (Schult.) Greene	8.2
Rose species	<i>Rosa</i> spp.	7.1
Wild tomato	<i>Solanum triflorum</i> Nutt.	7.1
Yellow sweetclover (includes white sweetclover)	<i>Melilotus officinalis</i> (L.) Pall. and <i>M. albus</i> Medik.	5.8
Wormseed mustard	<i>Erysimum cheiranthoides</i> L.	5.2
Wild oat	<i>Avena fatua</i> L.	4.0
Alfalfa	<i>Medicago sativa</i> L.	3.9
Biennial wormwood	<i>Artemisia biennis</i> Willd.	2.9
Prostrate knotweed (includes striate and erect knotweed)	<i>Polygonum aviculare</i> L., <i>P. achoreum</i> S.F. Blake, <i>P. erectum</i> L.	1.9
Scentless chamomile	<i>Matricaria perforata</i> Mérat	0.9

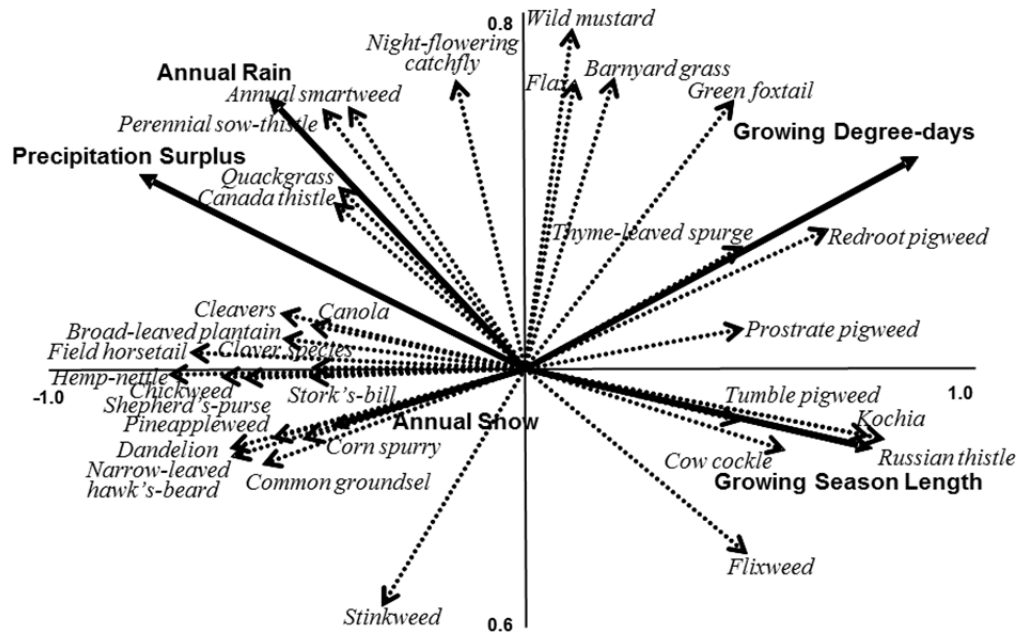


Figure 3. Ordination based on redundancy analysis (RDA) where species are constrained by climatic factors. Only species with more than 20% of their variance explained by the first two axes are included on the ordination (see Table 2 for scientific names of species).

Weed distributions

Russian thistle has a clearly defined distribution that is restricted to the warmer, drier areas (Figure 4A). It is primarily found in southern areas and it is absent in northern Alberta. This introduced species is well established, and has been recognized as a problem weed on the Canadian Prairies since the late 1800s (Fletcher 1897). The distribution has not changed since the 1970s (Leeson et al. 2005). An increase in temperature may allow range expansion of this species.

Kochia is also found in warmer, drier areas (Figure 4B). However, the northern edge of the range is not as clearly defined as that of Russian thistle. The range of kochia has expanded since the 1970s (Thomas and Leeson 2007), partially due to increased growing season length. Bioclimatic modeling has shown that an increase in temperature would result in the northern range expansion of this species (Beckie et al. 2011; Olfert et al. 2011, this volume).

Wild mustard is found in the highest frequency in Manitoba, an area with both high annual rainfall and a long growing season (Figure 4C). An increase in temperature and precipitation may lead to increased abundance. Field horsetail and

hemp-nettle are found in the northern wetter, cooler areas (Figure 4D and E). If moisture is the limiting factor, a precipitation increase may allow range expansion. If temperature is the limiting factor, a warmer climate would restrict their range.

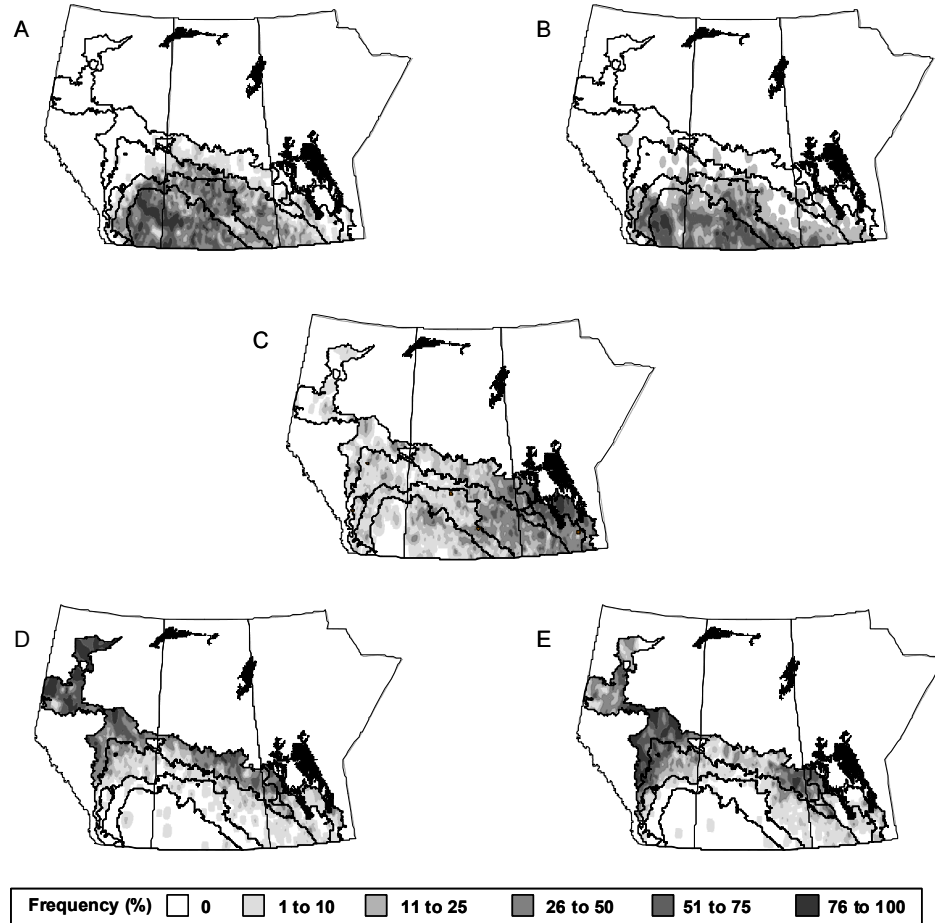


Figure 4. Distributions of (A) Russian thistle (*Salsola tragus* L.), (B) Kochia [*Kochia scoparia* (L.) Schrad.], (C) wild mustard (*Sinapis arvensis* L.), (D) field horsetail (*Equisetum arvense* L.), and (E) hemp-nettle (*Galeopsis tetrahit* L.).

Conclusion

Climate change is expected to alter the distribution and abundance of many of the common weed species in the Prairie provinces. Over half (32) of the 60 most common weed species had more than 20% of the variance in their distribution

associated with climate; 16 of the 20 most common weed species (not including crop volunteers) had more than 30% of the variance in their distribution associated with climate. Growing degree-days is the main climatic factor determining weed species distribution. Therefore, a warming climate will likely impact the distribution and abundance of a number of important agricultural weeds, such as kochia and barnyard grass. Because precipitation patterns across the Prairies under a warming climate are less predictable than that of temperature, further analysis needs to be conducted to determine whether temperature or precipitation is limiting the distribution and abundance of the climate change-sensitive species identified in this study.

Sources of materials

¹ArcView software 9.3, ESRI Incorporated, 380 New York Street, Redlands, CA 92373-8100.

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The papers in this volume of *Topics in Canadian Weed Science* were presented at a symposium held during the Canadian Weed Science Society - Société canadienne de malherbologie (CWSS-SCM) meeting in Charlottetown, Prince Edward Island in November 2009. The topic of "Climate Change and the Canadian Agricultural Environment" was chosen as the symposium theme because across Canada the effects of climate change are being seen as the decades pass. Weed scientists, who conduct periodic weed surveys, have noted the spread of several noxious and invasive species into areas where they were not noticed previously and farmers sometimes have difficulty achieving control in different agricultural situations. Crops that were not previously grown in some parts of Canada are now productive and adding greatly to local crop rotation options. Part of this change could be attributed to improved genetics and breeding of cultivars for cooler climates but some may be due to climate change. Although some research has been done in Canada, the potential and profound effects of climate change as it impacts weeds has not been given the level of research required to allow producers to prepare and adapt. How we control weeds and plant pathogens in crops, the impact of changes on crop management can all exert demands for new weed science technologies.

In this symposium, we asked our speakers to discuss the evidence of changes due to climate change and the challenges in weed science that will have to be met. They have presented the evidence for climate change, viewpoints about climate change and potential effects in Atlantic Canada as well as recent studies on changes in weed, disease and insect distribution in crops in western Canada. The studies are some of the earliest conducted in agriculture in Canada and emphasize the need to have more research conducted on basic principles to improve our understanding of mechanisms involved and possible ways to solve problems that may arise.



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P.O. Box 674
Pinawa, Manitoba R0E 1L0
Canada

ISBN 978-0-9688970-8-9



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