Agriculture and climate change: implications for environmental sustainability indicators

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Abstract

Agricultural activities have many effects on the environment, including effects on soil and air quality, water quality and quantity, contamination, and wildlife habitat. Agriculture and Agri-Food Canada has calculated a set of science-based agri-environmental indicators (AEIs) to provide information on environmental conditions in agriculture and their trends. The indicators are based on models developed from scientific understanding of the interactions between agriculture and the environment and are calculated using mathematical models to integrate information on soils, climate, and landscape with agricultural activity or practice information from the Canadian Census of Agriculture. Several AEIs were selected to explore the effects of climate change on agri-environmental sustainability. Based on the analysis in this study, those indicators that would likely decrease in their performance in the future include: risks of soil erosion from wind and water, soil salinization, water quality, nitrogen contamination, phosphorous contamination, pesticide contamination, and particulate matter emission rate. The one indicator found to likely improve with climate change was the greenhouse gas budget. In addition, the impacts of climate change were difficult to assess for several indicators as their values are more affected by both agricultural and non-agricultural factors, as well as lack of knowledge. AEIs are important tools to measure climate impacts and to indicate the success of adaptation to those impacts. This research is only emerging, however, and many knowledge gaps exist.
Keywords: indicators, environment, climate, agriculture, Canada.

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1 Introduction

The world's climate is now shifting more rapidly and differently than previously experienced. Effects are being observed in many sectors, especially those sensitive to weather and climate, such as agriculture. This is the basic and critical reason for concern about the issue of agri-environmental effects of climate change. Climatic effects on agriculture are of many types and include changing production levels of crops and livestock, risks of insects, weeds, and diseases, and changing demands for the products. Climate also affects environmental conditions, such as soil, air, water and biodiversity. These current and future possible effects are producing many responses, and will lead to the need for even further adaptation by agricultural producers.

Agriculture provides indispensable strategic commodities, such as food, fiber, and bio-energy. The world-wide demand for food, fiber, energy and water is increasing, making the role of agriculture in future even more vital. Agriculture can protect the environment's goods and services for society. The goods and services are numerous and can be categorized as: provisioning services, regulating services, and cultural and supporting services. Examples include sustenance of commercial activities, regulating natural cycles, and protecting and enhancing biodiversity. Agricultural activities, however, can also cause damage to environmental goods and services. These damages may also reduce the short to long term productive capability of agriculture. Agriculture's economic progress, in turns, depends on environmental health (e.g. soil, water). These linkages of agriculture, climate and the environment are explored in this paper.

How can agri-environmental indicators be used and developed to measure sustainability in the context of climate change? The related question is: can agri-environmental indicators be used to measure (and possibly predict) the impact of climate change directly?

2 Agriculture and environment: key linkages to indicators

Agroecosystems are dynamic, with various components constantly entering and leaving the system [1]. Such transfers interact with the broader environment. Agricultural activities have many effects on the environment, including effects on soil and air quality, water quality and quantity, contamination, and wildlife habitat. Following a recommendation by the federal and provincial Ministers of agriculture, the Agriculture and Agri-Food Canada initiated a project called NAHARP – National Agri-Environmental Health Analysis and Reporting Program. Under the auspices of this project, a set of science-based agri-environmental indicators (AEIs) were developed to provide information on environmental conditions in agriculture and their trends [2]. These indicators were intended to provide to policy makers and public-at-large reliable science-based information on the current state and changes in the conditions of the environment in agriculture at a national and regional scales. The indicators are based on models developed from scientific understanding of the interactions between agriculture and the environment. AEIs are calculated using mathematical models to integrate information on soils, climate, and landscape with agricultural activity or practice information from the Canadian Census of Agriculture. AEIs are valuable tools for assessing the capability of agriculture and agri-food systems to work towards sustainability.

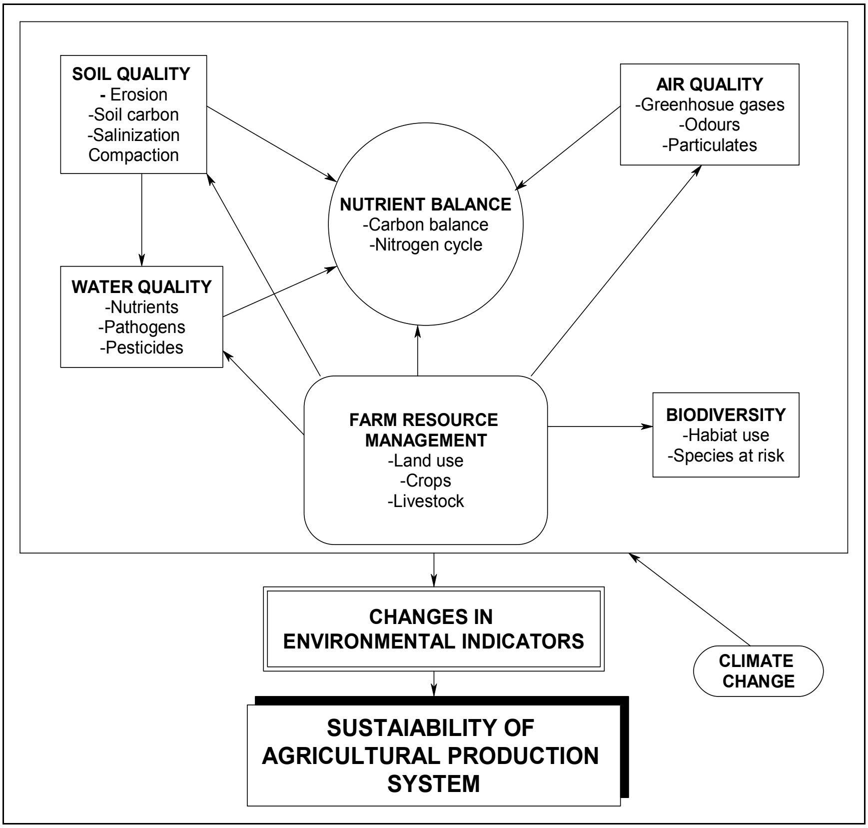

Figure 1: Relationship between AEIs and health of agricultural production system. (Source: adapted from [1].)

3 Measurement using indicators

Agriculture and Agri-Food Canada selected indicators using Driving Force – Outcome – Response framework [1]. Driving forces reflect the changes that have on the potential to affect agricultural production system. Those based on outcomes include the consequence of the driving force indicators. These can be both positive gains to social benefits (food security, employments, ecological benefits) or adverse (negative). Responses include those indicators that result in producer or consumer behaviour as a result of output indicators. The NAHARP included six categories of indicators as shown in Table 1.

Table 1: Measurement of NAHARP indicators.

Indicator Group	Indicator	Measure
Soil Quality	Risk of soil erosion	Potential for soil loss in surface runoff under prevailing landscape and climatic conditions and management practices
	Risk of wind erosion	Potential for soil loss by wind erosion under prevailing landscape and wind conditions and management practices
	Soil organic carbon	Change in organic carbon levels in soils under prevailing management practices
	Risk of tillage erosion	Potential for soil redistribution under prevailing landscape conditions and tillage and cropping practices
	Risk of soil compaction	Potential for change in degree of soil compaction of clay-rich soils
	Risk of soil salinization	Potential for change in degree of soil salinity estimated from land use, hydrologic, climatic, and soil properties
Water Quality	Risk of water contamination by nitrogen	Potential for nitrogen levels in water leaving farmland to exceed Canadian drinking water standards
	Risk of water contamination by phosphorus	Potential for phosphorus to move off farmland into surface water
Agricultural greenhouse gas emissions	Agricultural greenhouse gas budget	Emission levels of nitrous oxide, methane and carbon dioxide from agriculture production systems
Agro-ecosystem biodiversity	Availability of wildlife habitat on farm land	Number of habitat-use units for which habitat has increased, remained constant, or decreased
Production Intensity	Energy use	Energy content of agricultural inputs and outputs
	Residual nitrogen	Difference between amount of nitrogen added to farm soils and that removed in harvested crops
Environmental farm management	Soil cover by crops and residue	Number of days per year when soil is left exposed
	Management of farm nutrients and pesticide inputs	Adoption of best management practices for handling fertilizer, manure and pesticides

Source: adapted from [1].

4 Expected changes in climatic patterns and sensitivity of AEIs

The world's climate is shifting fairly rapidly and effects are being observed. Climatic factors, especially droughts and excessive moisture, are major forces behind production changes in agriculture, especially on a year-to-year basis [3]. Climate changes are especially noticeable in high latitude and mid-continental locations such as the Canadian prairies. Future climate changes in such areas are also expected to be much greater than in other areas and much faster than in the past. Several studies have documented past climate changes in Canada. For example, Qian *et al.* [4] found significant changes in several agro-climatic variables across Canada. These trends included increases in growing season length, frost-free days and heat units. A larger percentage of climate stations had significant changes during more recent periods, indicating an increase in rate of change.

In the agricultural prairies, average annual temperatures have been rising since climate stations were established in the 1880s. Sauchyn [5] showed that the mean annual temperature of several stations with long records had an average increase of 1.6°C from a low of 0.9°C at Calgary in the west to a high of 2.7°C at Swift Current in the central prairies. Using a station at Saskatoon in the northern central agricultural region, Beaulieu and Wittrock [6] found statistically significant warming with spring and winter showing the greatest increases in temperature during 1964 to 2008. The frost-free season has lengthened by about 30 days. Annual precipitation has decreased, but the trend is not statistically significant. The station receives a large amount of bright sunshine, but that amount is decreasing, especially during the summer.

Future possible changes in agro-climates for the study area for a period centered on the 2050s (2040–2069) are summarized by Wheaton [7]. Some estimated projections include: growing degree-days (base 5 C) increase about 25 to 50%; growing season length increases by about 15 to 50 days; moisture deficits increase by 60 to 140 mm; the area with aridity indices less than 0.65 increases by 50%; standardized precipitation index changes are minimal; the Palmer Drought Severity Index shows that the worst droughts become more frequent and intense. These climatic shifts would have important implications for agricultural productivity, for adaptation, and for agricultural effects on the environment.

First, we must determine which AEIs are sensitive to climate change. This sensitivity affects their usefulness for the purpose of assessing climate change effects. Several AEIs use climatic variables directly in their modelling and therefore have climate sensitivities. Climate affects agro-environmental sustainability directly through variables such as temperature, precipitation, and wind. Indirect effects occur through climate impacts on vegetation, insects and diseases, for example. Several AEIs were selected to give examples of indicators that can be used to explore the effects of climate change on agri-environmental sustainability. A list of those sample indicators is provided in Table 2, along with their model parameters, identification of those parameters with links to climate change, comments and sources. The models selected are risks of wind erosion, water erosion, soil salinization, particulate matter emission rate, ammonia emissions, and wildlife habitat availability.

5 Implications of climate change for the agricultural environment

Climate change is currently having effects on agriculture and agriculture is adapting to these changes. The effects and adaptation, in turn, are having effects on the sustainability of agriculture. This section addresses the question, what effects may climate change have on the sustainability of the agriculture environment? We use AEIs as measures of this sustainability.

Table 2: AEI models, their component parameters and climate links.

AEI	Model parameters	Parameters with direct or indirect link with climate	Comments
Wind erosion risk	Soil erodibility, soil ridge roughness, climate, equivalent vegetative cover factors	Direct through the climate factor	Climate factor is directly proportional to the cube of the wind speed and indirectly proportional to soil moisture
Water erosion risk	Rainfall and runoff erosivity, soil erodibility, topography, cover management, and conservation practice factors	Direct through runoff factor	Same value was applied for all census years. The runoff factor is a function of the kinetic energy and maximum 30 min intensity of the storm
Risk of soil salinization	Presence and extent of salinity, topography, drainage, aridity, surface cover/ vegetation factors	Direct through aridity factor and indirect through surface cover factor	Aridity depends on the balance between precipitation and evaporation
Particulate matter emission rate	Activity and emission factors	Direct and indirect, through effect of seasonality	
Ammonia emissions	Two methods used to estimate NH_3 emissions	Direct and indirect, through effect of seasonality	Amount of fertilizer used may vary with climate variations. Highest emissions are in May and lowest in January
Species specific wildlife habitat availability	Land cover category, habitat use value, habitat capacity	Direct and indirect, through effect of seasonality	Climate influences the type of vegetation and water for habitat

Source: Wheaton *et al.* [8].

AEIs are a measure of changes in the environment that are associated with agricultural activities. They also can be useful tools to indicate the changes of the agri-environment in the context of a shifting climate. We use a tabular approach to summarize possible trends of AEIs under future climate change, with application to the Canadian prairies agricultural region. Tables 3 to 5 include the main selected AEIs used in Canada, descriptions of their current trends, comments regarding these trends, and future possible trends. We also include comments regarding possible results that may occur if adaptation to deal with adverse trends is not successful.

Table 3: Implications of climate change for soil health-related indicators, with emphasis on the Canadian Prairies.

AEIs	**Current Trends in Performance of AEIs***	**Comments re Current Trends**	**Future Estimated Trends of AEIs with Climate Change**	**Comments re Future Possible Trends (without successful adaptation)**
Soil Health	Overall improvement, good to desired status	Improved land management, mainly conservation and no-till practices, and increased forage and permanent cover crops.	Unknown	Status depends on many factors, such as rate of climate change, adaptation success, and regional variation
Soil Erosion (water, wind, tillage)	Improved performance	Changes are mostly due to the decreased tillage erosion in the Prairies	Declining performance	Higher rainfall amounts, drought, and decreasing snow cover protection contribute to poor performance
Soil organic carbon	Improved performance	Moved from average to good status	Unknown	Depends on capability to deal with droughts and excessive moisture, for example. Could improve due to increasing growing season and heat units. Adding permanent cover also increases soil organic matter.
Soil salinization	Improved	Moved into the desired range	Decline	Driven by increased wet and dry events
Contamination by trace elements	Stable in average status range	Calculated only for 1981 and 2006	Unknown	To be determined

*Based on Eilers *et al.* [2] and Wheaton *et al.* [8].

The AEIs used include farm land management (i.e., agricultural land use, farm environmental management, soil cover, and wildlife habitat), soil health (i.e., erosion, organic matter, trace elements, salinity), water quality (nitrogen, phosphorous, coliforms, pesticides), air quality (i.e., particulate matter, ammonia, greenhouse gases), and the food and beverage industry (i.e., energy use and greenhouse gas emissions, water use and packaging) [2]. We have added the issue of water quantity it is a prerequisite for agricultural activities. Sub-components of water quantity would include groundwater, reservoirs, constructed storage ponds, wetlands, and stream flows.

Table 4: Implications of climate change for water quality- related indicators, with emphasis on the Canadian Prairies.

AEIs	Current Trends in Performance of AEIs*	Comments re Current Trends	Future Estimated Trends of AEIs with Climate Change	Comments re Future Possible Trends (without successful adaptation)
Water Quality	Good status, but overall declining	Main driver is increased nutrient application	Decline	Nutrient application could increase with increasing demand related to climate effects, while water availability at some critical periods dwindles.
Nitrogen contamination	Desired status	Prairies only, decline in other regions	Decline	Seasonal variability of wet and dry periods impacts crop yields and lessens the ability to match nutrient application to crop nutrient uptake. Intermittent wet periods would result in declining performance in the prairies
Phosphorous contamination	Decline	Prairies only, due to continuous cropping and increases in livestock production	Decline	Seasonal variability of wet and dry periods impacts crop yields and lessens ability to match nutrient application to crop nutrient uptake. Increased storm frequency could result in increased runoff and declining performance
Coliform contamination	Decline	Prairies only due to increasing livestock numbers, improvement elsewhere	Decline	As for current trends and as above
Pesticide Contamination	Decline	Dealing with pests and diseases continues to be a challenge	Decline	Increases in insects, diseases and weeds are expected with associated expected increases in management by pesticides

* Based on Eilers *et al*. [2] and Wheaton *et al.* [8].

6 Agri-environmental changes with droughts and excessive moisture and adaptation options

Some of the largest changes in the agricultural environment are expected to occur with climate extremes, such as droughts and excessive moisture. Wheaton *et al.* [8] briefly discussed the possible effects of climate extremes, such as droughts and floods, on agri-environmental sustainability. They propose that some of the largest changes in agri-environmental sustainability are likely to

Table 5: Implications of climate change for air quality related and other indicators, with emphasis on the Canadian Prairies.

AEIs	Current Trends in Performance of AEIs*	Comments re Current Trends	Future Estimated Trends of AEIs with Climate Change	Comments re Future Possible Trends (without successful adaptation)
Air Quality	Average status with gradual improvement	Related to improvements in land management	Unknown	Effects on agriculture to deal with increasing demand and other trends require consideration
Greenhouse gas budget	Improved	Due to improved land management, especially in the Prairies	Improve	Improved land management, depending on many drivers. Production of energy crops may reduce greenhouse gas footprint of agriculture.
Particulate matter emissions	Improved	Due to improved land management, especially in the Prairies	Variable	As above, except for the effect of increased droughts
Biodiversity-Wildlife Habitat on Farmland	Slight decline	Due to loss of natural and semi-natural land cover and intensification of agricultural operations from 1986 to 2006	Unknown	Status depends on rate and severity of climate change. Increased heat and moisture stresses could result in shifting land uses to more pasture in drier areas and more crop land in moister areas
Water Supply and Use	No current AEI Presumed declining performance	This issue is added by the authors. Insufficient information regarding water supplies and use. Surface water supplies in the prairies are being over-allocated. Droughts and floods continue to be problematic	Supply declines, demand increases	This issue is added because of the concerns regarding climate change effects on water scarcity and excessive moisture

*Based on Eilers *et al.* [2] and Wheaton *et al.* [8].

occur with changing extremes of climate. The more severe droughts and rainstorms would increase the likelihood of wind and water erosion of soil. These events in turn could lead to increased contamination of water bodies and decreased water quality.

The risk of soil salinization would increase with increased wet and dry sequences. An amazing dry to wet event occurred during the spring of 2010 when many climate stations switched from record low precipitation totals to record high precipitation totals during the summer of 2010 (e.g. Beaulieu and Wittrock [6] for Saskatoon, Saskatchewan).

The projected increasing frequency, intensity and area of droughts in interior continental North America and other similar areas would likely increase competition and conflicts over water. How will these changes affect agriculture and agri-environmental sustainability?

Drought events affect both agricultural productivity and agri-environmental sustainability. Drought also affects the adaptation options that are applied to deal with drought effects. Several beneficial farm practices and the associated environmental farm planning deal with drought. As drought lengthens from short events to multi-year events, the harmful effects increase. Examples include reduced and changed vegetative cover, increased weed pressure, increased wind and water erosion of soil. Beneficial Management Practices (BMPs) such as conservation tillage does help reduce risk of soil erosion during droughts, but multi-year droughts would likely reduce vegetation cover so much that even more careful management practices are required. Multi-year severe droughts may have adverse effects beyond the capabilities of current adaptation. Another effect of drought on management practices is the effect of leaving more land fallow in efforts to reduce input costs. This economic effect can then have negative effects on sustainability.

Current trends of AEIs are compared with possible trends of AEIs with climate change adaptation. Improving adaptation would also improve trends in the AEIs. The AEI reporting also provides a wealth of possible adaptive response options that would improve the performance of AEIs and thus of environmental sustainability [2]. These adaptations would likely act to improve the performance of agriculture in dealing with climate change impacts.

7 Using agri-environmental indicators in the context of climate change

What data, information, and methods are needed or need to be developed to adequately assess environmental sustainability under climate change? The methods would ideally include integrative models for climate and earth systems, agricultural and environmental impact models, and adaptation models (including land use and agricultural practices). AEIs are very suitable for estimating future possible directions in sustainability because they use science-based mathematical models. Several use climate parameters, such as temperature, precipitation, and wind, so they can be used in conjunction with climatic scenarios to estimate future AEIs, and thus indicate future sustainability. The future trends would then point to the need for adaptation options, their type, and the urgency of application.

Scales of a wide range in both space and time ideally need to be addressed by the data and methods. Impacts and adaptations occur on short term (e.g. daily) to long term bases (monthly to decades). Wittrock and Wheaton [9] documented impacts and adaptations occurring on both short to long term for the 2001 to 2002 drought in the Canadian Prairies. Adaptation methods to be assessed for their effect on agricultural sustainability (as measured through AEIs) include those currently used through to novel options that may be used in the future.

In terms of spatial scales, AEIs are suited to a wide range of scales ranging from perhaps the farm level ecosystem, provincial and national levels. For example, wind erosion risk can be calculated at the field level and then aggregated upward. AEIs should be checked for this capability of dealing with various scales.

Several AEIs use climatic parameters directly in their models. Other AEIs may be developed to use climatic parameters, if possible. This section explores the methodology of selected Canadian AEIs to demonstrate their possible sensitivities to climate. Climate affects environmental sustainability both directly through factors such as temperature, precipitation, and wind and indirectly through effects on vegetation, insects and disease pests, for example. The sensitivity of AEIs to climate may be explored by calculating the changes in an AEI for each unit of change in a relevant climatic element. This has not been done for AEIs, to the authors' knowledge, and would be a step towards assessing the effect of climate change on AEIs.

8 Conclusions

Literature regarding the topic of agri-environmental sustainability as influenced by climate change appears sparse. Therefore, understanding is at an early stage, and research gaps are numerous. Many concepts were explored in this paper, as suitable for preliminary assessments of complex topics. Main messages include:

- Research frameworks that consider agri-environmental sustainability need to be built and/or further developed to deal with the climate change questions. The number of factors to be included is high and their interactions are complex. Qualitative assessments could be much improved by the application of quantitative modeling as integrated assessment systems.
- AEIs can be used now and require further development to assess vulnerabilities of agri-environmental sustainability to both current and future climate change. This direction enhances the links of science to operations, planning and policy.
- Possibilities of more vulnerable aspects of agri-environmental sustainability were noted and further work is needed to verify these preliminary findings and check other areas of agri-environmental change.
- Estimates of future impacts would be valuable to test adaptation scenarios (e.g., BMPs) to plan for advances in adaptation decisions, operations, and policy in order to achieve improvements in agri-environmental conditions.

Climate change will likely have considerable effects on the agri-environment and agricultural productivity. The research concerning these relationships is an early phase to advance the rationale, research frameworks and directions for questions regarding the effects of the convergence of evolving agriculture, climate, and environmental systems. Agri-environmental sustainability and agricultural productivity are threatened by climate change. When climate change converges with changes in agriculture and the economy, results may or may not contribute towards sustainability. Agri-environmental sustainability determines the future of food, economic and societal security.

References

[1] AAFC (Agriculture and Agri-Food Canada). National Agri-Environmental Health Analysis and Reporting Program (NAHARP): 2003 Technical Workshop. Ottawa. 2003.

[2] Eilers, W., R. MacKay, L. Graham and A. Lefebvre (editors). Environmental Sustainability of Canadian Agriculture: Agri-Environmental Indicator Report Series, Report #3. Agriculture and Agri-Food Canada, Ottawa, Ontario. +235 pp. 2010.

[3] Williams, G. D. V., R. A. Fautley, K.H. Jones, R.B. Stewart, E.E. Wheaton. Estimating Effects of Climatic Change on Agriculture in Saskatchewan, Canada. In: Parry, M.L., T.R. Carter, N.T. Konjin (Editors), *The Impact of Climate Variations on Agriculture,* pp. 221-371. Vol. 1. Kluwer Academic Publishers, Dordrecht/Boston/London. 1988.

[4] Qian, B., S. Gameda, X. Zhang, R. De Jong. Changing Growing Season observed in Canada. Climatic Change 112:339-353. 2012.

[5] Sauchyn, D., Prairie Climate Trends and Variability. Chapter 3 in Sauchyn, D., H. Diaz, and S. Kulshreshtha (editors). The New Normal, the Canadian Prairies in a Changing Climate. Canadian Plains Research Center, University of Regina, Regina Saskatchewan. 2010.

[6] Beaulieu, C. and V. Wittrock. Examination of Climate Trends and Extremes: A Saskatoon Case Study. Prepared for Environment Canada. Saskatchewan Research Council, Saskatoon, SK. 2010.

[7] Wheaton, E., Agriculture. In D. Sauchyn (lead author), E. Barrow, X. Fang, N. Henderson, M. Johnston, J. Pomeroy, J. Thorpe, E. Wheaton and B. Williams, Saskatchewan's natural capital in a changing climate: an assessment of impacts and adaptation. Prairie Adaptation Research Collaborative, Regina, Saskatchewan, SRC# 11299-1E09, 166p. 2009.

[8] Wheaton, E., W. Eilers, S. Kulshreshtha, R. MacGregor, and V. Wittrock. Assessing Agri-environmental Implications of Climate Change and Agricultural Adaptation to Climate Change. SRC Publication No. 10432-1E11. Saskatoon: Saskatchewan Research Council. 2011.

[9] Wittrock, V. and E. Wheaton, Towards Understanding the Adaptation Process for Drought in the Canadian Prairie Provinces: The Case of the 2001 to 2002 Drought and Agriculture. Prepared for the Government of Canada's Climate Change Impacts and Adaptation Program. Saskatchewan Research Council (SRC) Publication No. 11927-2E07 SRC, Saskatoon, SK. 129pp. 2007.