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Environmental Sustainability of Agriculture Stressed by Changing Extremes of Drought and Excess Moisture: A Conceptual Review

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Abstract: As the climate changes, the effects of agriculture on the environment may change. In the future, an increasing frequency of climate extremes, such as droughts, heat waves, and excess moisture, is expected. Past research on the interaction between environment and resources has focused on climate change effects on various sectors, including agricultural production (especially crop production), but research on the effects of climate change using agri-environmental indicators (AEI) of environmental sustainability of agriculture is limited. The aim of this paper was to begin to address this knowledge gap by exploring the effects of future drought and excess moisture on environmental sustainability of agriculture. Methods included the use of a conceptual framework, literature reviews, and an examination of the climate sensitivities of the AEI models. The AEIs assessed were those for the themes of soil and water quality, and farmland management as developed by Agriculture and Agri-Food Canada. Additional indicators included one for desertification and another for water supply and demand. The study area was the agricultural region of the Canadian Prairie Provinces. We found that the performance of several indicators would likely decrease in a warming climate with more extremes. These indicators with declining performances included risks for soil erosion, soil salinization, desertification, water quality and quantity, and soil contamination. Preliminary trends of other indicators such as farmland management were not clear. AEIs are important tools for measuring climate impacts on the environmental sustainability of agriculture. They also indicate the success of adaptation measures and suggest areas of operational and policy development. Therefore, continued reporting and enhancement of these indicators is recommended.

Keywords: environmental sustainability; agricultural sustainability; environmental indicators; climate change; climate extremes; drought; excess moisture; Canadian Prairie Provinces

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1. Introduction

Considerable changes in climate variables relevant to agriculture and the environment have already occurred and have been documented [1–3]. For the agricultural portion of the Canadian Prairie Provinces, where this study was conducted, these agro-climatic changes include longer growing seasons, more crop heat units, decreasing snow-cover area, changes in precipitation from snow to rain during winter months, and warmer winters. Future changes for the prairie agricultural region indicate continued and perhaps accelerated trends in these variables and many others [1,4]. An increase in climate extremes, including droughts, excess moisture, and heat waves is expected for the Canadian Prairies [5,6]. These extremes can often have adverse effects on the environmental sustainability of agriculture. More recent work also confirms that future drought characteristics (frequency of droughts, duration, and intensity) show increases over the southern prairies [7]. Increases in such extremes would have adverse effects on the environmental sustainability of agriculture. The effects of droughts and excessive moisture on environmental sustainability are of special concern, and are the subject of this paper.

Agriculture is an important part of the economy of the Canadian Prairie Provinces of Alberta, Saskatchewan, and Manitoba. The agriculture and agri-food system of these provinces consists of several industries including primary agriculture, farm input and service providers, food and beverage processing, food distribution, as well as retail, wholesale, and food service industries. In Canada, this sector contributed CAD$108 billion (or 6.6% of Canadian gross domestic product) and employed 2.3 million workers [8]. Much of this production activity occurs in the Prairie Provinces. Primary production is a key part of this system as it affects the other components of the regional economy [9].

Although agriculture is important to the economy, environmental impacts must also be considered for achieving sustainability. Agriculture has many effects on the environment and these effects determine the environmental sustainability. Environmental sustainability is defined as sustainability of ecological services that are provided by the ecosystems [10]. Humans depend upon these services directly or indirectly. A strong environmental sustainability would label any practice unsustainable if the natural ecosystems are put to alternative uses, such as conversion of forest ecosystems to agricultural ecosystems. A more practical definition of environmental sustainability requires that those ecosystems and ecosystem services that are essential to humans be conserved to the point of a minimum safe standard. Examples of effects include those on soil and air quality by the use of different tillage and cropping systems, and those on water quality related to the use of fertilizer and pesticides. Climate trends and extremes are expected to affect air, land, and water resources, and knowledge of these effects are crucial to achieving sustainable agricultural production and food and water security. The effects of excess moisture and drought are especially important, as they can have more pronounced impacts on the environmental sustainability of agriculture than gradual increases in temperature. For example, droughts reduce the protection of soil moisture and vegetation, and erosion can result. Excess moisture and flooding can result in water run-off leading to erosion of soil and damage to vegetative cover that protects the soil. Flooding can also damage the storage areas of fertilizer, manure, and pesticides, releasing them as contaminants into the environment. In this paper, we explore the effects of climate change on the environmental sustainability of agricultural systems, with emphasis on the extreme events of droughts and excess moisture. Therefore, our main objective is specifically to assess the effects of future drought and excess moisture on selected agri-environmental indicators. No other investigations have addressed this topic, to our knowledge.

By 1999, the member countries of the Organization for Economic Cooperation and Development (OECD), including Canada, noted that establishing a key set of agri-environmental indicators (AEIs) that could be useful for member countries was important [11]. In Canada, Agriculture and Agri-Food Canada (AAFC) reports on a set of science-based AEIs using mathematical models showing the interactions between agriculture and the environment [9,12]. These two reports are the latest in the series of Canada's agri-environmental reporting. Therefore, they are the basis for the AEIs we have selected for use, as well as associated trend information. This reporting series and their AEIs are not intended for use with climate change scenarios, but their use may be for strategic adaptation to drought and excess moisture.

Wall and Smit [13] noted that agricultural sustainability and climate change adaptation strategies support one another and that ecosystem integrity is needed for sustaining agricultural production. However, Wheaton et al. [14–16] were the first, according to the authors' knowledge, to assess the possible changes in agricultural sustainability (using AEIs) as expected under climate change, and this study builds upon and expands that work. They found several of the AEIs to be sensitive to climate change and reported a possible decline in the performance of AEIs with climate change for soil erosion, contamination, soil salinization, and water quality categories.

2. Data and Methods

Environmental sustainability indicators of agriculture considered here were based on changes in the set of science-based AEIs developed by Agriculture and Agri-Food Canada [9,12]. The AEIs report agri-environmental performance under four main categories: soil quality, water quality, air quality, and farmland management. Each category has set of indicators addressing sub-themes within the category (e.g., from the soil health theme, sub-indices include soil erosion, soil organic matter, trace elements, and salinity). Many of the indicators can be integrated within climate change studies either directly or indirectly. Directly, these indices can be calculated using climate change scenario data and compared with values obtained under the observed climate record.

Our study methods included literature reviews, development of a conceptual framework, examination of the possible relationships, sensitivities and responses of selected AEIs to climate by examining their mathematical structures. These approaches were used to suggest possible directions of future trends in AEIs with increases of drought and excess moisture under continued climate change. In the remaining sections, the selected AEIs are described, along with an assessment of their future status.

The AEIs selected for this study were those for the soil quality, water quality, and farmland management themes. We added two more indicator types because of their relevance, one for desertification and another for water supply and demand. AEIs were selected for their utility in assessing the possible effects of current and future drought and excess moisture. We examined the mathematical models (factors affecting the relationship among stimulus that causes a change in the AEI level) of each AEI as the first step in choosing them [15]. The AEIs that contain climate variables in their mathematical models are the most clearly sensitive to climate, and therefore either are directly driven by and may have strong relationships with climate change. We determined the nature of the relationships by the types of climate variables used (e.g., temperature, precipitation) in the indicator and whether the relationship with climate was linear or more complex and direct or inverse. Some AEIs for the category of soil quality are good candidates for exploring the direct effects of drought and excess moisture on the environment. Examples include the wind and water erosion, salinity, and particulate emission models as they include climate variables. Where it was not possible to assess indices due to a lack of direct use of climate variables in the models, climatic effects were indirectly implied from ecosystem assessments of changes in vegetation, insects, and diseases, for example.

Although drought and excess moisture affect most aspects of environmental sustainability, we focused on AEI categories and their indicators for soil quality, water quality, farmland management, and water supply and demand, as guided by our conceptual framework (Figure 1), expertise and available literature. From the conceptual framework, we analyzed how the four AEI themes would be affected by changing climate extremes starting with the knowledge of the main characteristics of future possible drought and excess moisture events, as summarized from the literature.

Drought and excess moisture events are expected to become more common in the future on the Canadian Prairies [5,7]. The frequency, intensity, and extent of moderate to extreme droughts are projected to increase. At the other extreme, the review also found agreement that the frequency of severe storms and unusually wet periods is also projected to increase, leading to the conclusion that wet times will become wetter and dry times will become drier, with several driving forces supporting this finding.

Regarding drought, four main characteristics of future possible droughts in the Canadian Prairies were found: (1) increased intensity of dryness, driven by increased evaporation potential with higher temperatures and longer warm seasons; (2) droughts of 6–10 months and longer become more frequent by the 2050s; (3) the frequency of long duration droughts of five years and longer more than doubles in the future to 2100; and (4) decade-long and longer droughts increase by triple in frequency to 2100 [5,6]. The finding of future possible increase in droughts is confirmed by other work that finds increases in drought characteristics in the Canadian Prairie Provinces, especially over the southern study region [7].

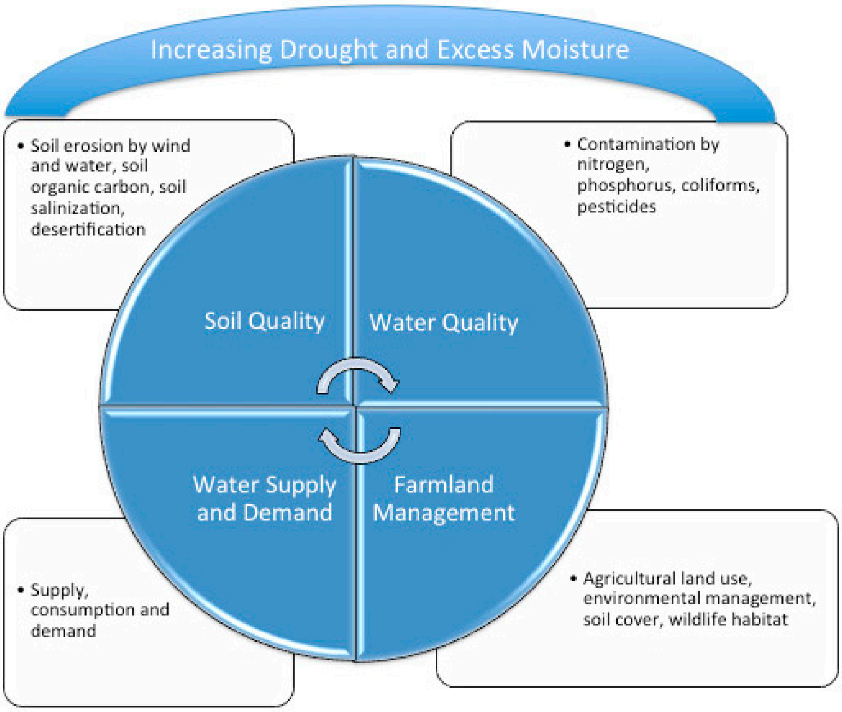

Figure 1. Framework for integrating the effects of changing climate extremes increasing droughts and excess moisture with selected main categories and sub-components of environmental sustainability of agriculture.

Shifting of climate zones poleward with higher temperatures also indicates the occurrence of drought in areas farther north of their usual positions in the study area. Worst-case scenarios should also be considered because of the severe and multiple effects of droughts. Mega droughts have occurred in the past in the Canadian Prairies [17], and it is therefore expected that droughts will be pushed to greater severity with climate warming.

In the context of future trends in the AEIs, it is important to ask: what are the future projections of extreme precipitation events and associated excessive moisture conditions? The IPCC (Intergovernmental Panel on Climate Change) [18] has reported on managing the risks of extreme climate events globally. The report indicates that the frequency of heavy precipitation will increase in the 21st century over many parts of the world. They gave this projection a 66–100% chance of occurring and found that this trend is particularly the case in the high latitudes.

The Canadian Prairie agricultural area has experienced extremely wet conditions in the past and these are projected to increase. Saskatchewan holds Canada's record wettest hour under the current climatic conditions when 250 mm rainfall occurred at Buffalo Gap in the south central area [19]. The largest area eight-hour event in the Canadian Prairies was the rainstorm of 3 July 2000 around Vanguard in southwest Saskatchewan. This storm brought about 375 mm of rainfall, exceeding the average annual precipitation of 360 mm, and caused severe flooding [20]. The projected changes to precipitation amounts in Canada for 2041–2070 show an increase in maximum precipitation in the range of about 10–20% for the prairies for the 20-year return period of one-day precipitation [21]. This means an increase from 40–60 mm (1941–1970) to 48–72 mm for the 20% increase.

Although the work of [17] for the prairies focused on droughts, the climate indices (i.e., Palmer Drought Severity Index and Standardized Precipitation Index) over the future period to 2100 show some very high values, indicating wet periods for a range of Global Climate Model results. For example, some of the future wet periods appear to be as excessive as the wet period of the 1970s. The review of future possible extremes suggested that the overall prairie climate would become drier, but with substantial year-to-year variability, including an increased chance of heavy precipitation and very wet periods [5,6]. The next section provides an assessment of the possible changes in AEIs with projected increases in drought and excess moisture.

3. Results

Descriptions of the environmental sustainability of agriculture as affected by drought and excess moisture are provided in this section for several AEIs. The indicators are in four main categories, soil quality, water quality, water supply and demand, and farmland management (Figure 1).

3.1. Possible Future Trends in AEIs for Soil Quality

Four main AEIs for the soil quality theme are discussed here, namely soil erosion, soil organic carbon, soil salinization, and desertification.

3.1.1. Soil Erosion by Wind and Water

Soil erosion occurs through the action of wind and water, as well as tillage. The soil erosion AEIs had overall improved performances in recent decades in the prairies, indicating reductions in erosion risk between 1981 and 2011 [12]. This trend is mainly due to improved land management, such as adoption of minimum to no-tillage practices, reduced use of summer fallow, and increased forage and cover crops [9]. Recent decades, however, have had severe and extensive droughts, such as in 1999 to 2004 [22], 2008 to 2010 [23], and 2015 [24]. The 2015 drought was found to be likely an outcome of human-influenced warm spring conditions and naturally forced dry weather from May to July. Droughts can result in considerable soil erosion by wind. At least 32 incidents of blowing dust were documented between April and September 2001. This number of incidents was high as it was exceeded only once during the 1977–1988 period of dust storms. Although the wind erosion was severe, it would have been much worse without the increase in soil conservation practices [22]. These events make it clear that drought can result in soil erosion even with the adoption of improved land management practices.

The greater evaporation rates, lower soil moisture, and decreased vegetation cover under droughts result in increased risk of soil erosion (Table 1). This means that management practices to reduce the soil erosion risk would become even more important in the future. Descriptions of future wind speed changes are rare, but Price et al. [25] project little change in wind speed, on average for the prairie semiarid region, with slight reductions in mean summer wind speed of 0.14 m/s for the medium emissions scenario for the 2040–2069 period. However, they did find increases of mean spring wind speed of 0.11 m/s for this scenario and time. Spring is an important time for increased wind erosion risk, as the vegetation cover is not yet well established and the soil is more exposed. Wind speed was a very important factor in the wind erosion component of the AEI as the relationship is direct and cubic [15,26]. The risk of future wind erosion in the province of Saskatchewan, Canada, was estimated to continue to increase with rising temperature and potential evapotranspiration [26].

Agriculture and Agri-Food Canada's assessment of the environmental sustainability of Canadian agriculture found that higher rainfall in eastern provinces, such as Ontario and Quebec, contributed to the lower performances of soil quality indicators [9]. This relationship between higher rainfall and soil quality is useful in assessing future effects in the prairies. Here, drought conditions can shift very quickly to wet conditions. Recent years have shown intense rainfall and severe flooding in several areas of the Prairie Provinces [27]. There were very wet conditions, especially in some parts, in 2010, 2011, and 2012. Spring 2010 was the wettest among the 1948–2012 period, at 64% greater than the areal average for the prairie climate region. Spring 2012 was the third wettest spring, at 52% higher than average. Summer 2010 was also very wet, with a total precipitation amounting to the fourth highest on record at 40% above average. Summer 2012 had the sixth highest areal average precipitation [28]. The heavy rainstorms and high amounts of accumulated precipitation resulted in many excess moisture problems, including more agricultural land being under water than ever recorded. Problems of excess moisture were persistent, lasting from October 2010 to July 2011 for many areas [27]. Intense rainfall events tend to contribute to runoff and increasing soil erosion (Table 1) and do not ease drought conditions as much as gentler rains.

Table 1. Potential effects of increasing droughts and excessive moisture on trends of soil quality indicators.

Soil Health Indicator	Climate Linkage (Direct and Indirect)	Effects of Increased Droughts	Effects of Increased Excess Moisture	Comments Regarding Other Factors
Soil erosion by wind	Wind, temperature and precipitation, soil moisture, vegetation cover	Reduced soil moisture and vegetation cover which increase erosion risk	Increased precipitation intensity can destabilize soil particles	Decreasing snow cover increases exposure to erosion
Soil erosion by water	Precipitation intensity, vegetation cover	Water erosion risk decreases	Increased heavy rainfall increases potential for soil erosion	Heavy rainfall on frozen soil increases erosion risk
Soil organic carbon	Temperature, precipitation, vegetation cover	Reduced vegetation production reduces carbon	Run-off increases carbon losses	Temperature increases tend to increase carbon losses
Soil salinization	Aridity (temperature and precipitation balance), vegetation cover	Evaporation concentrates salts. Reduced vegetation cover can increase salinization	Elevated water tables can increase salinization	Increased variability with drought/wet shifts increases salinization risk
Contamination by trace elements	Precipitation intensity	Possible increased concentrations may occur	Increases	Climate effects estimations require further investigation

The summer of 2011 in Southeastern Saskatchewan provided a good example of several heavy rainfall events [29]. April–June in 2011 had 150 to over 200% of normal precipitation amounts. Multiple rainfall events of 20 mm or greater occurred, and a severe 1:100 year rainfall event occurred on 17 June 2011. These events resulted in unprecedented floods in the Souris River Watershed, causing state of emergency declarations in communities of Weyburn and Estevan. The community of Roche Percee had to evacuate almost every home [30]. Therefore, these extreme precipitation times not only resulted in the flooding of agricultural land with several implications for environmental sustainability, but they also resulted in a loss of homes and other infrastructure (e.g., roads, culverts, and bridges). The damage to infrastructure meant that soil erosion also occurred, though this was more difficult to assess. The impacts to environmental sustainability are discussed with the specific indicator addressed in the following sections. Examples include soil quality (e.g., water erosion of soil) and water quality (e.g., run-off contaminants).

Further changes to snow cover are also expected and have already occurred. Snow cover protects the soil from erosion risk. Northern Hemisphere spring snow cover extent has significantly decreased over the past 90 years and the rate of decrease has accelerated over the past 40 years. An 11% decrease in April snow cover extent has occurred for the 1970–2010 period compared with pre-1970 values. These trends are mainly a result of increasing temperatures [31]. This means that the soil was exposed to wind and water erosion for an increasing length of time in the recent past, and this trend is projected to continue with further warming. Alternatively, snow-melt contributes to overland run-off and can result in water erosion of soil. Recent work finds extensive decreasing trends of snow-water equivalent in Canada related to increasing temperature. The mean size of the decreasing trend for December–April is -0.4 to -0.5 mm/y [32]. Estimates of future possible snow cover changes are challenging because of the complex response of snow cover to warming, but widespread decreases in snow cover duration are projected across the Northern Hemisphere [33]. Implications for the soil erosion AEI are very uncertain because of this complexity, but effects of the continued trend of decreasing snow cover extent should be considered in measures to protect the soil against wind and water erosion.

Intense rainfall events and higher total precipitation accumulations result in greater run-off, with eroded and flooded land (Table 2). The increased water erosion and the flooded land can result in many problems for environmental sustainability of agriculture, including contamination by pollutants of various types resulting in water quality problems.

Table 2. Selected agri-environmental indicator (AEI) categories, indicators, their relationships with climate, and possible future climatic effects related to drought and excess moisture.

Group	Indicator	Measure	Sensitivity to Climate	Links with Climate-Related Changes
Soil Quality	Risk of soil erosion by water	Surface run-off	Strong	Climate change may result in aridity in some parts of the prairies which would increase the probability of surface run-off
				Higher variability in precipitation and incidence of wet events would lead to higher incident of soil erosion
	Risk of wind erosion	Soil loss through wind events	Strong	Future increases are expected with simulated increases in spring wind speed
	Soil organic carbon	Organic carbon level in soil	Medium	Future changes with climate change are not clear because of the interacting effects of management practices
	Risk of soil salinization	Degree of soil salinity	Strong	Climate change may increase salinity from variations of precipitation and dry events
	Contamination by trace elements		Strong	Increased wet and dry periods affect contamination
Water Quality and Quantity	Risk of water contamination by nitrogen	Nitrogen level released by farms into water bodies	Weak	Water run-off containing nitrogen associated with soil erosion is affected by variable precipitation
	Risk of water contamination by phosphorus	Phosphorus level released by farms into water bodies	Weak	Water run-off containing phosphorus associated with soil erosion is affected by variable precipitation
	Water supply and use	Water availability and use	Strong	Climate change would likely impart a reduction in supply, but an increase its demand
Farmland management	Soil cover by crops and residue	Duration of exposed soil	Strong	Vegetative cover is affected by climate change
	Management of farm nutrients and pesticide inputs	Application of organic and inorganic nutrients and pesticides	Medium	Favorable wetter conditions may lead to increased nutrient use. Climate change may lead to increased pest and diseases and the need for their management

3.1.2. Soil Organic Carbon

Other AEI components of soil quality include the tillage erosion risk indicator, soil organic carbon change (SOCC) indicator, the risk of soil salinization indicator, and the risk of soil contamination by trace elements. As indicated earlier, only selected indicators can be considered. The SOCC indicator is affected by land management changes, including the effects of tillage practices, summer fallow frequency, cropping types, and land-use changes. The current trend of the SOCC indicator showed an improved performance from average to a good status as most of the cropland had increasing soil organic carbon from 1981 to 2011. Spatial patterns over the Prairie Provinces to 2011 ranged from no change to large increases in Alberta, large increases over much of Saskatchewan, and mostly moderate increases in Manitoba. The use of reduced tillage practices and reduced summer fallow area was an important influence in this change in the prairies. The Century model was used to predict the rate of change in organic carbon content in soils [9,12].

An important aspect of soil is its carbon storage capacity, which can affect the atmospheric concentrations of carbon dioxide. The level of soil organic carbon would be susceptible to climate change extremes. For example, under a drought period, organic biomass is low which would affect the level of soil organic carbon. Similarly, if land management under climate extremes includes more permanent cover, soil organic carbon would tend to increase because of plant-derived inputs to soils. Vegetation cover is adversely affected by both droughts and flooding and may result in at least short-term decreases in soil organic carbon. Moreover, depending on other constraints, temperature increases would tend to increase soil decomposition loss of carbon [34].

One of the developments needed for the SOCC indicator is to include soil erosion aspects in the model. Even low rates of soil erosion can decrease soil organic carbon [9]. Soil erosion risk increases during droughts and heavy rainfall, so the effects of these extremes should be incorporated into their modeling. Another limitation of the SOCC indicator is that the effects of past (and future) temperature increases do not appear to be assessed and discussed in the reporting by [9]. The Century model does use monthly temperature and precipitation data, so this assessment is possible and is recommended.

3.1.3. Soil Salinization

The risk of soil salinization in the Prairie Provinces decreased from 1981 to 2011, and over this period the land area in the very high-risk class decreased by 2%. The spatial patterns of risk of soil salinization (RSS) on the prairies showed no change to decreased risk in Alberta and Manitoba and large areas of decreased risk in Saskatchewan. The improvements were mostly related to land management, including decreased summer fallow area, and increased area under permanent cover [35]. Again, as for the SOCC, the impact of changing land use practices on the risk of soil salinization dominated, and climate change did not appear to be considered in the modeling for this AEI and results. However, growing season moisture deficits were a factor in the calculations, but the significant yearly variation in the risk of soil salinization was not considered in the indicator [35]. Such sensitivity of RSS to changes in moisture deficits could be determined. Our early estimate of the possible effects of future increased droughts and excessive moisture is the reduced performance of the RSS indicator (Table 2).

3.1.4. Desertification

A risk of desertification indicator is under development [36], and is included here because of its relevance to the topic. This indicator is not included in the most recent AEI reporting [12]. Desertification is the degradation of land in arid to dry sub-humid regions. The preliminary results indicate that average soil erosion rates were usually below the soil tolerance level, meaning that desertification risk due to erosion was low as of 2006 in the Prairie Provinces [36].

Desertification risk increases with soil erosion, losses of soil organic matter, and fluctuating soil salinity [36]. Climatic extremes have the potential to increase all of these factors as discussed previously, and therefore can increase the risk of desertification. Research indicates that the area of land at risk of desertification in the Prairies could increase by about 50% between conditions of 1961–1990 and the 2050s [37]). The World Meteorological Organization [38] states that climate change may exacerbate desertification and soil salinization through alteration of spatial and temporal patterns in temperature, rainfall, solar radiation, and winds. The threat means that the indicator development is recommended to be completed (including climate drivers) and implemented as led by Agriculture and Agri-Food Canada.

The agricultural area of the Canadian Prairies has a large semi-arid climate zone in southwest to west central Saskatchewan and corresponding regions in Alberta. The remainder of the area is mostly classified as dry sub-humid. These climate classifications are based on the Thornthwaite method using a moisture index with the input of monthly mean temperature and precipitation data [39]. These are the climate zones targeted in the desertification definition [37]. A warming climate is expected to expand these dry zones northward in the prairies to cover even greater areas.

3.2. Possible Future Trends for Water Quality

Climate change can be a major instrumental factor affecting water quality, both for surface as well as ground water (Table 2). These changes would occur as a result of two types of developments, both related to climate change. (1) Climate change would likely reduce water quantity (as described later), which would result in changes in flow regimes influencing the chemistry, hydro-morphology and ecology of regulated water bodies [40]. (2) Agricultural activity would face longer growing seasons combined with reduced water availability, with new crops suited to drier [41], warmer conditions. In addition, wetlands that play an important role in water purification may also dry up during such heat events and longer evaporative seasons. The longer growing season and cropping changes could increase the use of fertilizers with subsequent leaching to watercourses, rivers, and lakes, increasing the risk of eutrophication and loss of biodiversity [42]. Many information gaps exist regarding the effects of climate change (e.g., cyclical variability between wet and dry periods) and these are important to quantify to meet the needs of flood control and water quality improvements, for example [43].

Changes in water quality during storms, snowmelt, and periods of elevated air temperature or drought can cause conditions that exceed thresholds of ecosystem tolerance and, thus, lead to water quality degradation [44]. Such precipitation extremes can pose significant risks to water quality outcomes, resulting in a degradation trend of drinking water quality and potential health impacts [45]. At the same time, the impacts of drought and excess moisture are superimposed onto other pressures on water resources [46] and can exacerbate the other pressures. Such pressures may include market pressures, pest, and disease infestations, and effects on producer incomes from other bottlenecks in the agricultural and food complex [8].

3.3. Possible Future Trends in Water Supply and Demand

Water supply and demand are considered (even though they are not included in Canada's AEI reporting series) because as they are critical for environmental sustainability of agriculture. Water demand for agricultural purposes is expected to increase in the future unless conservation measures are in place. Facing periods of frequent droughts, more farmers would lean towards having irrigation on their farms. However, whether this demand would be met or not depends on water availability and its competing uses [47–49].

Water quantity under climate extremes would be affected through reductions in the water stored in glaciers and snow cover. These water sources are currently declining and this trend is projected to continue, e.g., [50]. This trend reduces water availability especially during warm and dry periods (through a seasonal shift in streamflow, an increase in the ratio of winter to annual flows, and reductions in low flows) in regions supplied by this source [51]. Where storage capacities are not sufficient, much of the winter runoff will be lost to the oceans, and this will create regional water shortages.

In addition to surface water, future changes in climate extremes could affect groundwater. Longer droughts may be interspersed with more frequent and intense rainfall events. These changes in climate may affect groundwater through changes in their recharge and discharge [52]. The aquifers where water withdrawal is already higher than their respective recharge amounts would be even more vulnerable to climate change. Such high levels of withdrawals would reduce available quantities considerably [51].

3.4. Farmland Management

Under climate extremes, land management would be affected through changes in soil moisture, which is directly related to climate extremes. Management of soil moisture and water harvesting would be significant adaptation measures to cope during climate extremes. However, many producers may not anticipate and react appropriately to the occurrence of climate extremes and make appropriate adaptations. A survey by [53] shows that, even during serious drought and flood years, only one third of farmers in China were able to use farm management measures to cope with the extreme weather events. In the Prairie Provinces, a survey of producers regarding the 2001–2002 drought indicated that no producer had made any changes in their cultural practices in anticipation of the drought [54]. However, prairie producers are adaptable, and much adaptation occurred during and after the 2001–2002 drought. In this region, many producers have switched from intensive tillage practices to conservation tillage practices. In 1991, only a third of the cropped area was under conservation tillage methods, but by 2011 this area rose by 157% of the 1991 area, thus constituting 85% of the total area prepared for seeding [55].

The four main AEI categories considered here, along with their indicators, measures, estimates of their sensitivities, and relationships with a changing climate are summarized in Table 2. Several of the indicators are estimated to be fairly sensitive to climate extremes, including soil quality, water supply and demand, and portions of farmland management. The reasons for the indication of weaker relationships with climate may be somewhat related to the lack of understanding of the relation of climate variables with the key parameters describing environmental health.

4. Discussion and Conclusions

This paper was an attempt to explore the possible effects of future drought and excess moisture on the environmental sustainability of agriculture. Methods included examining the possible relationships and responses of AEIs to climate drought and excess moisture using the conceptual framework of Figure 1, by evaluating the relationship of AEI models with climate variables, and by using literature reviews. These approaches were used to suggest possible directions of future trends in AEIs with increased drought and excess moisture. The AEIs assessed were those for soil and water quality, and farmland management as developed by Agriculture and Agri-Food Canada [9], with additions of water supply and demand categories.

The estimation of any future occurrence is difficult with many limitations because of several unknowns. However, the projections using several different methods, including climate indices, climate models, and emission scenarios provide strong agreement of the findings of increased intensity and frequency of both future droughts and extreme precipitation (e.g., [6,7,17]). Measuring, monitoring, modeling, projecting, and communicating the characteristics of wet and dry climate extremes are becoming even more critical as the climate shifts and becomes less stable. Sufficient information is needed to guide planning for and implementation of effective actions to adapt to the impacts of climate extremes.

The critical issues of the effects of climate extremes on environmental sustainability of agriculture include effects on natural resources and their ecosystems, including soil quality, water quality, and water supply and demand. Results indicated the nature of future possible changes in AEIs as affected by trends in climate change and extremes. In order to meet the goal of environmental sustainability of agriculture, climate trends and extremes need to be carefully considered. Much better use of climate information and services are required to meet the goal of environmental sustainability of agriculture. The lack of consideration of climate change reduces the capability to adapt and increases vulnerability.

The possible future effects of climate change extremes examined here are conceptual, but are plausible based on the current data from climate science. Actual results may be lower, but they also might be much higher in terms of worst-case scenarios. Solutions for effects of climate extremes should also considered, especially those with the most serious consequences.

Soil quality, as measured by AEIs in the agricultural region of the Prairie Provinces, has showed an improving trend for the 1981–2011 period [12]. However, these AEIs have strong land management drivers, and the effects of climate trends and extremes are not clear. Results regarding the effects of climate change indicate possible declining performances for soil erosion, salinization, and desertification. Results regarding the effects of climate change for other soil AEIs such as soil organic carbon, contamination by trace elements, and farmland management have even less information. All of these AEIs require more work to fully assess the effects of climate change, especially extremes, such as drought and excessive moisture.

The AEIs are numerous with four main categories containing several indicators apiece as described in [12]. Therefore, many could not be addressed here, including air quality and biodiversity indicators. Alternatively, a critical indicator, that of water supply and demand, is not a part of the AEI indicator series by Agriculture and Agri-Food Canada [9,12]. However, water supply and demand was discussed here as a possible indicator, and we recommend it to be included in the AEI series. Next steps in the AEI assessments are recommended to include additional indicators and their relationships with climate change.

Results indicate that the performance of several indicators would likely decrease in a warming climate with more extremes of droughts and extreme moisture. These indicators include risks of soil erosion, soil salinization, water quality and quantity, and soil contamination. Thresholds of climate extremes, however, may be reached and result in accelerated negative performances of such indicators. The impacts of climate change are more difficult to assess for several indicators because of the effect of other factors, such as land management. AEIs are important tools to measure climate impacts on environmental sustainability of agriculture. They also indicate the success of adaptation measures and of required policy development. The climate change risks to environmental sustainability of agriculture require much more attention.

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